Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: SUSTAIN Model Pilot Study

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Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9:

SUSTAIN Model Pilot Study

Prepared for:

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Submitted by:

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EXECUTIVE SUMMARY

Stormwater is one of the biggest threats to the water quality and ecological health of the waters of Puget Sound, both fresh and marine. The overall goal of this planning study is to develop a cost estimate for implementing stormwater BMPs and low impact development (LID) techniques in previously developed areas of WRIA 9. The focus of the planning study is the development and testing of the coupling of watershed hydrology models (a long-standing centerpiece of stormwater planning in the Puget Sound region) with a relatively new stormwater BMP modeling and planning tool developed by the U.S. EPA - the SUSTAIN model (**S**ystem for **U**rban **S**tormwater **T**reatment and **A**nalysis **IN**tegration).

As part of the planning study, stakeholders have been engaged in developing BMP cost and design assumptions as well as in the development of in-stream flow and water quality goals that allow the coupled models to be used to optimize the amounts and types of BMPs that are needed to best meet specific targets at the least cost. Another overall goal of the planning study is the evaluation of costs associated with additional development and redevelopment in the future (2040) as well as the potential cost implications of climate change within the same future time horizon. Planning level cost estimates for the Puget Sound basin will also be developed via extrapolation.

This report documents the results, conclusions and recommendations of a pilot study conducted on a small urban catchment in Newaukum Creek used to help identify a path forward to using SUSTAIN to develop retrofit cost estimates for WRIA 9.

The goal of this pilot study is to document the basic model coupling framework, the selected BMPs and the overall treatment design (treatment trains), BMP design and cost assumptions, and the method of application of the models to a small pilot catchment.

The documentation of the method of application of the models in this pilot study and the associated presentation of results is intended to inform the approach that will be used to extend the modeling effort beyond the initial pilot study catchment. Specific objectives of this pilot study are identified below:

- Document the BMPs to be considered and the associated treatment trains
- Document the BMP design specifications used in the SUSTAIN model
- Document the cost assumptions used in the SUSTAIN model
- Document the methods used to estimate residential rooftop, commercial parking and road surfaces and assumptions regarding treatment of runoff from these impervious and associated pervious areas
- Document the application of the hydrologic target used in the SUSTAIN cost-effectiveness optimization
- Document the extrapolation of the cost-effectiveness results to biological and water quality improvements

In general, the most effective combinations of the types and numbers of BMPs were not 100 percent effective in restoring hydrologic conditions to those that might occur if the pilot study catchment was restored to fully-forested conditions. Assuming catchment soils have low permeability (Till Scenarios; BMP infiltration rate of 0.3 in/hr), the percent effectiveness (i.e., the relative ability of a selected scenario solution to reduce the annual average number of High Pulse Counts [HPCs] that occur under current land conditions) ranged from 31 to 55 percent (i.e., up to a 55 percent reduction of HPC; from 19 to 8).

Total 30-yr life-cycle costs generally reflected the maximum effectiveness achieved in any particular Till scenario and ranged from $4.8 to $14.7 million (M) (roughly $20,000 to $65,000 per acre). The two most effective scenarios with respect to reduction in HPC (55% reduction in HPC at a cost of about $10.7 M) were Green+Gray treatment trains, one with cisterns and the other with rain barrels (although no rain barrels were selected in this solution), treating an additional 80 percent of the pervious surface runoff and assuming that none of the BMP infiltration returns to the catchment outlet (Scenarios 11 and 15). These scenarios were also relatively effective in reducing PEAK:BASE, an additional hydrologic indicator selected for use in this project which serves as an independent check on the potential for improvement in Benthic Index of Biotic Integrity (B-IBI) scores.

The cost breakdown for Scenarios 11 and 15 were very similar, with the private capital costs being slightly higher for Scenario 15 ($3.09 vs $2.13 M) and the total public costs being very similar ($10.85 vs $10.64 M).

Statistical models used to extrapolate improvements in hydrologic indicators to improvement in B-IBI scores indicated that the most optimistic improvement (linear regression 90% upper confidence) in B-IBI scores in the most effective scenarios might be as high as 76 percent of the maximum possible score (nominally 38 on the current scale of 10 to 50) to the most pessimistic improvement (90% lower confidence) of 17 percent of maximum – essentially no improvement. Logistic models have also been developed that provide probabilistic estimates of B-IBI score improvements. As an example, based on the most effective Till scenarios PEAK:BASE results indicate a probability of scores greater or equal to 40% of maximum (nominally 20 on the current scale of 10 to 50) were slightly higher than 50 percent.

Statistical extrapolations also suggested substantial improvements in water quality. However, effectiveness in reducing HPC did not always translate into effectiveness in reducing TSS/copper loads or concentrations. The most effective scenarios with respect to water quality improvements generally reduced TSS loads by 80 percent and copper and zinc loads by 30 to 40 percent. The frequency of exceedances of the state turbidity standard was also reduced by up to 85 percent. Dissolved copper concentrations were predicted to be relatively low and were not predicted to exceed the acute or chronic standard under current conditions. Zinc was predicted to exceed the acute standard under current conditions and the most effective Till scenarios based on HPC were predicted to effectively eliminate the exceedances of the acute zinc standard.

These statistical extrapolations incorporate uncertainly based on the data they were developed from, but do not include other sources of uncertainty such as the concern that bioretention BMPs may be net sources of some contaminants, particularly copper. The expected positive effect of these treatment scenarios is predicated on the design and construction of BMPs that do not themselves generate contamination, but rather effectively treat them through filtration, settling and dispersion through subsurface flow pathways that result in low (and generally non-hazardous) levels reaching groundwater systems and/or streams and rivers.

Scenarios were also evaluated assuming very poorly drained (Type D) soils that would require the use of underdrains in bioretention and porous parking BMPs, with no infiltration to native soil. These scenarios resulted in somewhat less to much lower effectiveness compared to the Till scenarios. As an example, the most effective selected "Best" scenario (45% effective) included a mix of onsite detention, roadside bioretention and detention ponds at a cost of $7.9 M. The analyses presented in this report regarding the Type D soil scenarios was limited to results of effectiveness and cost.

Based on initial evaluation and discussion of the results presented in this pilot study report by the Project Management Team and by participants at the upcoming workshop, the Project Management Team will move forward with modeling additional catchments, focusing on specific catchments throughout the basin that represent distinctly different types of land use/land cover. Discussions at the upcoming workshop will guide additional modeling or analysis that may be incorporated into the final version of this document. The next step of expanding the modeling effort beyond the pilot study catchment will become a larger effort to meet the overall objectives of this study – to develop planning level retrofit cost estimates for WRIA 9 and ultimately for Puget Sound.

1.0. INTRODUCTION

King County was awarded a Puget Sound Watershed Management Assistance Program Fiscal Year 2009 grant by Region 10 of the U.S. Environmental Protection Agency (U.S. EPA) to develop a stormwater retrofit plan for Water Resources Inventory Area (WRIA) 9 (King County 2010).[1] The goal of this grant-funded study was to develop a plan and associated costs to implement stormwater Best Management Practices (BMPs) in developed areas of WRIA 9 built primarily without stormwater controls. Another goal of the study was to extrapolate stormwater retrofit costs to all of the developed area draining to Puget Sound. This report documents the methods, results, conclusions and recommendations of a pilot study conducted on a small urban catchment in Newaukum Creek used to help identify a path forward to using SUSTAIN – a stormwater BMP modeling and planning tool developed with support from U.S. EPA – to develop retrofit cost estimates for WRIA 9.

1.1 Background

Stormwater is one of the biggest threats to the water quality and ecological health of the waters of Puget Sound, both fresh and marine.[2] The overall goal of this planning study is to develop a cost estimate for implementing stormwater BMPs and low impact development (LID) techniques in previously developed areas of WRIA 9. The focus of the planning study is the development and testing of the coupling of watershed hydrology models (a long-standing centerpiece of stormwater planning in the Puget Sound region) with a relatively new stormwater BMP modeling and planning tool developed by the U.S. EPA - the SUSTAIN model (**S**ystem for **U**rban **S**tormwater **T**reatment and **A**nalysis **IN**tegration).[3]

As part of the planning study, stakeholders have been engaged in developing BMP cost and design assumptions as well as in the development of in-stream flow and water quality goals that allow the coupled models to be used to optimize the amounts and types of BMPs that are needed to best meet specific targets at the least cost. Another overall goal of the planning study is the evaluation of costs associated with additional development and redevelopment in the future (2040) as well as the potential cost implications of climate change within the same future time horizon. Planning level cost estimates for the Puget Sound basin will also be developed via extrapolation.

The study area consists of the Green/Duwamish watershed and portions of the Central Puget Sound watershed that comprise WRIA 9, excluding the areas upstream of Howard Hanson Dam and the city of Seattle (Figure 1). Vashon-Maury Island, which is technically in WRIA 15, but is sometimes included in WRIA 9 for planning purposes is also excluded from the study area. Lands within Seattle are not included in the study area because a vast

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[1] http://your.kingcounty.gov/dnrp/library/water-and-land/watersheds/green-duwamish/stormwater-retrofit-project/stormwater-retrofit-workplan.pdf

[2] Ecology – Threats to Puget Sound (http://www.ecy.wa.gov/puget_sound/threats.html)

[3] U.S. EPA's SUSTAIN website: http://www.epa.gov/nrmrl/wswrd/wq/models/sustain/

majority of Seattle's lands within WRIA 9 are served by a combined sewer and stormwater system and a combined sewer overflow (CSO) control program is already underway in this area. The area of WRIA 9 upstream of Howard Hanson Dam is not included in the study area because it is primarily forested and maintained to protect Tacoma Public Utilities' water supply.

The total area being evaluated is approximately 280 mi^2 and includes a diversity of land cover and land use types. Land uses range from working forest and agricultural lands and low density residential uses outside of the designated urban growth area (UGA) to moderate to high density residential and commercial and industrial lands within the UGA (King County 2010). The study area population is projected to grow by about a quarter of a million people between 2000 and 2040. This population increase will result in the conversion of additional land for urban use, and the redevelopment of previously developed land for higher density use.

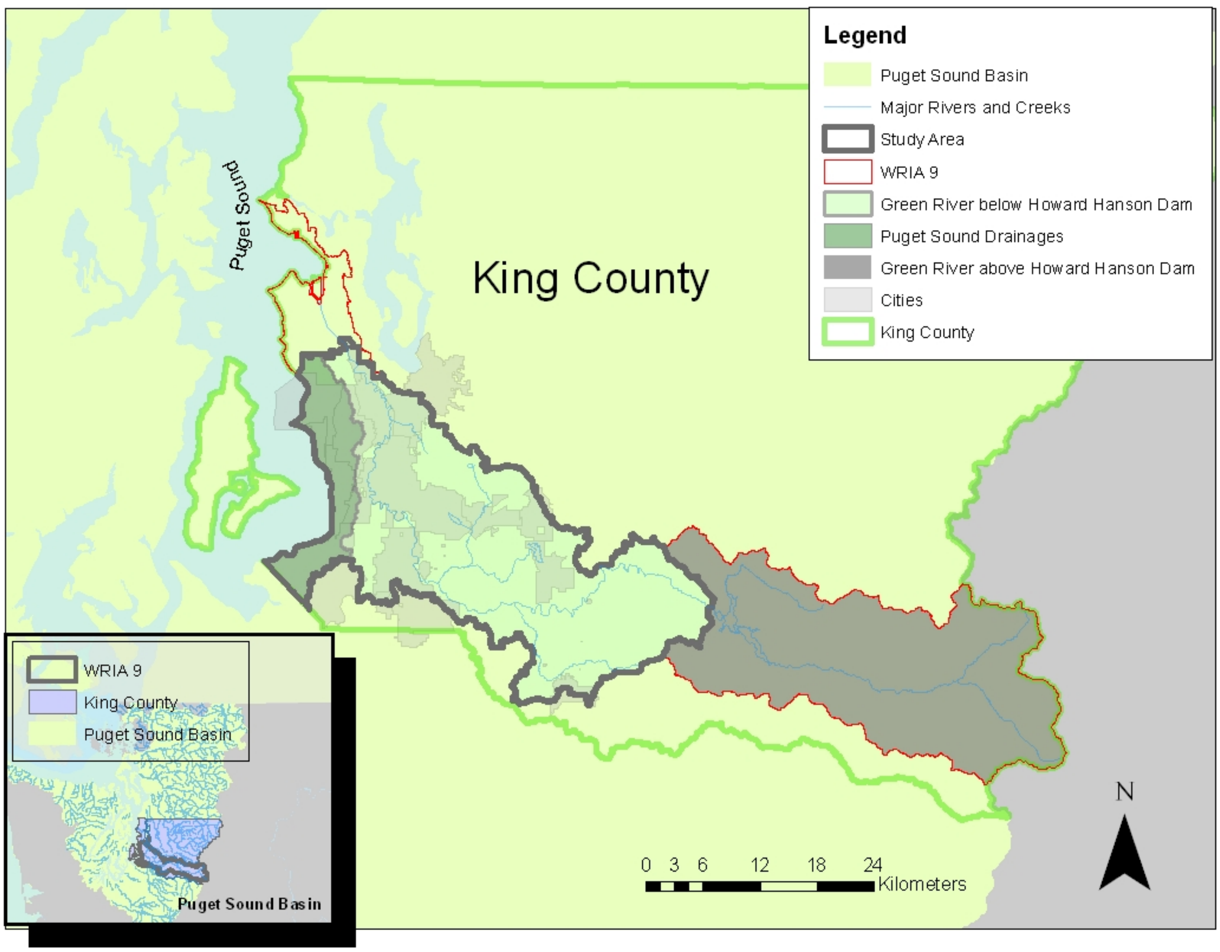

Figure 1. Map showing the project study area within Water Resource Inventory Area 9.

1.2 Pilot Study Goals and Objectives

The goal of this pilot study is to document the basic model coupling framework, the selected BMPs and the overall treatment design (treatment trains), BMP design and cost assumptions, and the method of application of the models to a small pilot catchment.

The documentation of the method of application of the models in this pilot study and the associated presentation of results is intended to inform the approach that will be used to extend the modeling effort beyond the initial pilot study catchment. Specific objectives of this pilot study are identified below:

- Document the BMPs to be considered and the associated treatment trains
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1.3 Pilot Study Area

The pilot study area that is the focus of this report was selected based on discussions held in Project Management Team (PMT) meetings[4] that initially evaluated eight sub-basins in WRIA 9 that were the focus of an earlier stormwater runoff and pollutant loading study. This earlier stormwater/pollutant loading study was conducted as part of the Green-Duwamish Watershed Water Quality Assessment (King County 2007). The initial focus on these eight sub-basins was due to their relatively small size (270 to 2,200 acres in area), the variety of relatively homogeneous land use types represented in each sub-basin (forested, agricultural, residential, commercial/industrial), and the availability of continuous stream gauging and water quality monitoring data collected at the outlet of each sub-basin that might be used for model testing and corroboration of results. Figure 2 shows the locations of the sub-basins in WRIA 9 that were considered for the development of a pilot study.

Ultimately, the smallest of these sub-basins, located in the headwaters of Newaukum Creek and including a portion of the city of Enumclaw, was selected for the initial development and testing of the SUSTAIN modeling framework (Figure 3). This sub-basin is dominated by high density residential uses and does not have large natural or constructed ponds or

[4] Project Management Team meetings, documents and workshop presentations and posters are available here: http://www.kingcounty.gov/environment/watersheds/green-river/stormwater-retrofit-project/documents.aspx

wetlands, which were considered to be complicating factors in several of the other basins that were considered.

The small size of the selected sub-basin was preferred because previous studies using SUSTAIN have determined that the aggregate BMP modeling approach planned for use in this study is most appropriate for watersheds with a low to moderate slope that are on the order of 50 to 150 acres in size (U.S. EPA. 2009). This is based on consideration of a model time step of one hour and typical rainfall-runoff travel time routing to the outlet of urbanized watersheds of various sizes.

Initially, the 270 ac sub-basin defined in the Green-Duwamish Water Quality Assessment was used in the development and testing of the modeling framework.[5] The initially selected sub-basin was represented by two catchments in the watershed hydrologic model. For this study report, the pilot study area is the 231.8 ac headwater catchment (NEW151) identified in Figure 3. This catchment has an estimated effective impervious area (EIA)[6] of 21.9 percent consisting of roads (5.2 percent) and rooftops and paved areas associated primarily with High/Medium Density Residential land use (14.4 percent), although lesser amounts of low density residential and commercial uses are also present (2.6 percent) (Table 1). The majority of the land cover in the basin is disturbed pervious area associated with High/Medium Density Residential land use (64.3 percent). The pilot study catchment is generally flat and surficial geology is about 50 percent Osceola mudflow, which is considered to have an infiltration capacity similar to glacial till and less infiltration capacity than glacial outwash in the Hydrologic Simulation Program-FORTRAN (HSPF) model used to simulate watershed hydrology.

[5] Developed and presented at the first 2-day SUSTAIN modeling workshop held in April of 2012.

[6] Effective Impervious Area (EIA) is the portion of total impervious area that conveys runoff directly into receiving waters. This concept recognizes that some forms of impervious land cover direct runoff to adjacent forested or grassed areas that would permit some infiltration and attenuation of direct runoff to receiving waters.

Table 1. Summary of Land Use/Land Cover and HSPF Hydrologic Response Units in the Newaukum pilot study catchment NEW151.

Land Use/Land Cover	Pervious/Impervious	Soil [a]	Slope		Area (acres)
Roads	Impervious	NA	NA	5.2%	12.1
Low Density Residential	Impervious	NA	NA	0.3%	0.7
High/Medium Density Residential	Impervious	NA	NA	14.4%	33.4
Commercial	Impervious	NA	NA	2.3%	5.4
Low Density Residential	Pervious	Till	Flat	6.9%	15.9
High/Medium Density Residential	Pervious	Till	Flat	64.3%	149.1
Commercial	Pervious	Till	Flat	2.3%	5.3
Grasslands	Pervious	Till	Flat	3.9%	9.0
Grasslands	Pervious	Till	Moderate	0.2%	0.4
Forest	Pervious	Till	Flat	0.2%	0.5
			Total Area	**100%**	231.8

NA = Not applicable. The impervious HRUs are not differentiated by underlying soil or slope.

[a] Soil type in the HSPF model is considered to be equivalent to glacial till, although the surficial geology of the catchment is primarily Osceola mudflow.

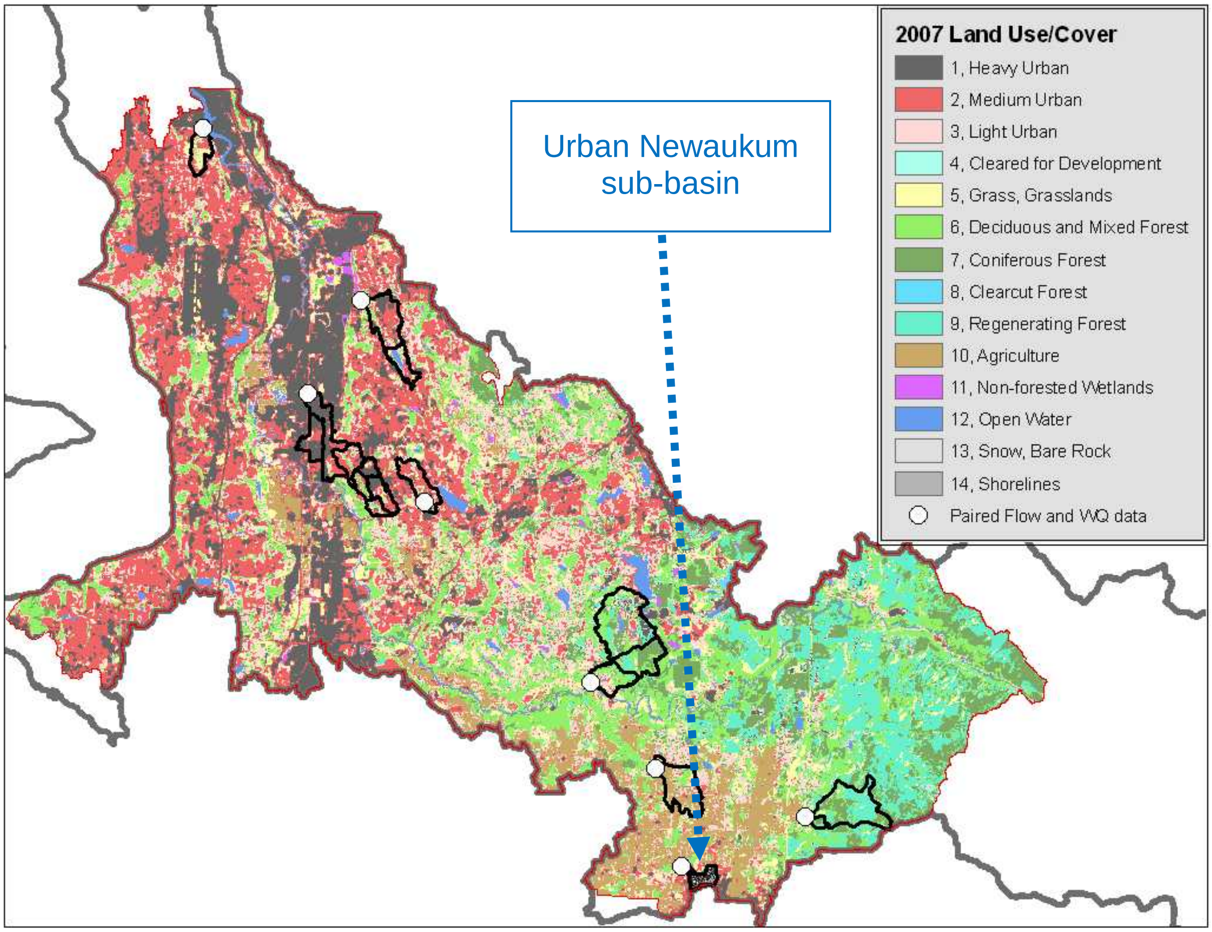

Figure 2. Map showing the locations of the initial eight sub-basins considered for a pilot study as well as the 2007 land use/land cover data used in the study.

Source: Central Puget Sound 2007 Land Cover Classification. Puget Sound Regional Synthesis Model (PRISM). Dr. Marina Alberti, Principal Investigator, Urban Ecology Research Laboratory (UERL), University of Washington, Seattle, WA.

http://urbaneco.washington.edu/wp/

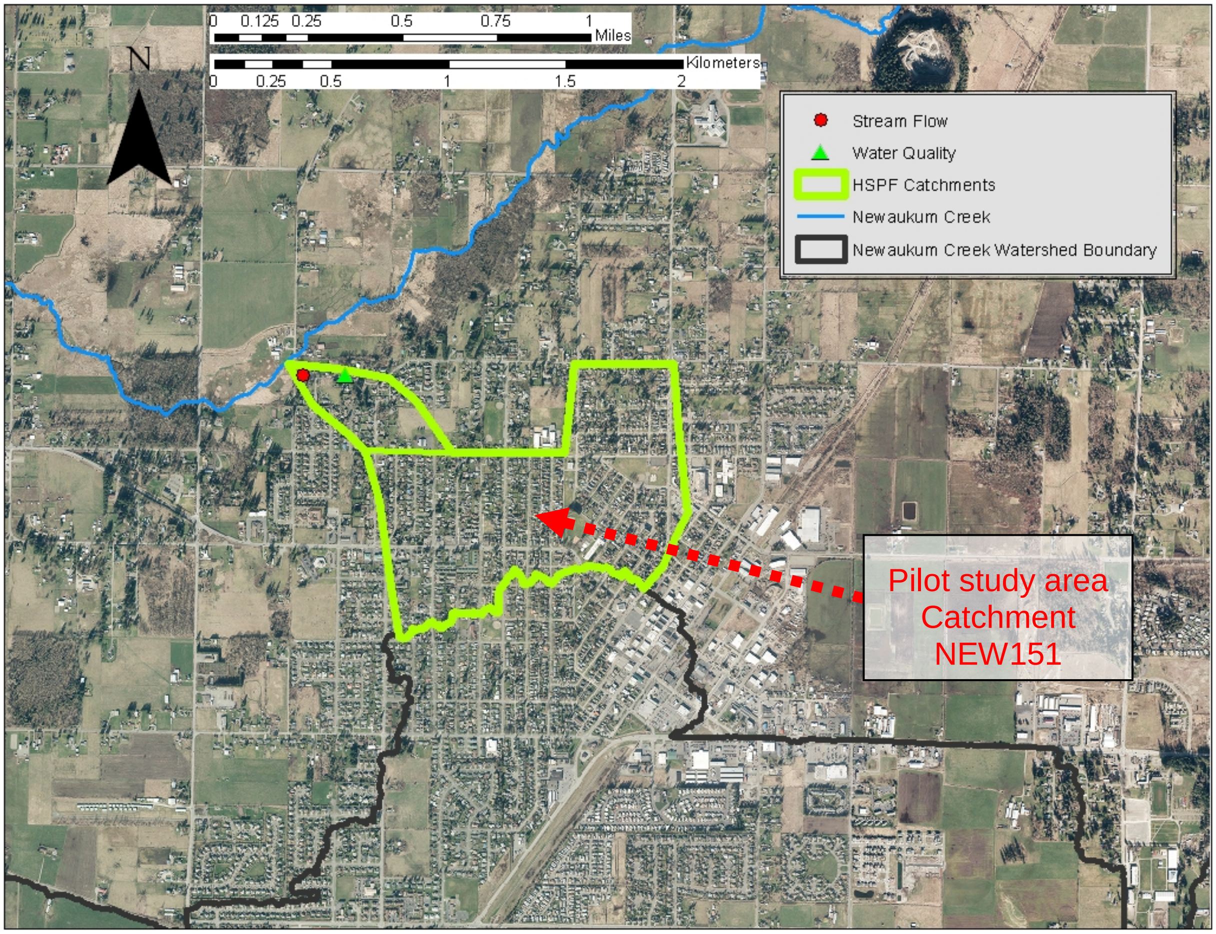

Figure 3. Map showing the urban Newaukum sub-basin and pilot study catchment.

Note: The larger upstream catchment (NEW151) is the pilot study catchment that is the focus of this report.

2.0. MODELING APPROACH

The modeling approach used in this pilot study is based on the capabilities and application guidance for the SUSTAIN model (U.S. EPA et al. 2009, Shoemaker et al. 2011, Lee et al. 2012). The SUSTAIN model allows for two distinct watershed hydrologic modeling approaches and two different approaches to simulating the effects of stormwater BMPs on the modeled watershed hydrology (and pollutant fate and transport). The latest release of SUSTAIN (Version 1.2, revised March 2013) was used in this pilot study.

The two watershed hydrologic modeling approaches are termed *internal* and *external*. The internal modeling approach involves the development of a watershed hydrologic model using the internal modeling capabilities of SUSTAIN. The internal SUSTAIN model is based on tested algorithms in Storm Water Management Model (SWMM) and HSPF. The external modeling approach involves the development and calibration of any continuous simulation hydrologic model that can produce unit area flow and pollutant time series files at an hourly or sub-hourly frequency from geographically defined areas known as hydrologic response units (HRUs).[7]

There are many models that might be suitable for use in generating external model inputs for SUSTAIN including HSPF or SWMM. Because King County has routinely used HSPF as a watershed modeling and basin planning tool and HSPF models of the study area had been developed previously (King County 2003), an external modeling approach using HSPF was selected for use in this study. The updating, calibration and testing of HSPF models for use in this study is documented in a separate report (King County 2013). Hourly HSPF model output for October 1948 through September 2009 for flow and total suspended solids (TSS) was provided as input to SUSTAIN.

The two approaches for simulating the effects of stormwater BMPs can be characterized as explicit and aggregate approaches. These approaches are not mutually exclusive and can be implemented in the same SUSTAIN model when using the external modeling approach.[8] The explicit approach represents particular BMPs at particular points within the watershed drainage network defined in SUSTAIN. The aggregate approach represents a combination of different types (and numbers) of BMPs that have no explicit location within the watershed. Because of the ultimate scale of interest in the overall study is on the order of 100's of square miles, the aggregate BMP modeling approach was used in this pilot study; consistent with the recommendation for application of SUSTAIN to overall study areas of this size (U.S. EPA 2009, see page 1-6).

The following sections describe the development of aggregate BMP templates, BMP cost assumptions, method used to estimate runoff generating areas to be treated by a particular BMP, selection of the cost-effectiveness optimization target, and the approach to the analysis and synthesis of SUSTAIN modeling results.

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[7] Hydrologic Response Units (HRUs) are land areas with similar combinations of surficial geology, land use, land cover and slope that have unique flow response characteristics in a watershed hydrologic model.

[8] The aggregate BMP modeling approach is not compatible with the internal modeling approach.

The approach to routing untreated pervious HRU subsurface flow and water that infiltrates through the base of the bioretention and porous pavement BMPs to an aquifer (a feature added in SUSTAIN version 1.2) that can be released back to the stream assessment point is also described below.

2.1 BMP Treatment Train Templates

As noted above, the aggregate BMP approach was adopted for this study. The BMPs that can be represented using the aggregate approach in SUSTAIN include rain barrels, cisterns, bioretention facilities, porous pavement and treatment ponds. Using the available suite of BMP simulation options, two BMP templates (or treatment trains) were proposed for use in this pilot study (Stakeholder Workshop #2, January 2012). Conceptually, the two treatment approaches can be characterized as a Natural Drainage (or Green) Treatment Train (Figure 4) and a Natural Drainage and Gray (Green+Gray) Infrastructure Treatment Train (Figure 5) which includes detention ponds[9] (the "Gray" treatment component) to treat the output from the Natural Drainage Treatment Train.

In general, the Natural Drainage Treatment Train consists of detention/storage of residential roof runoff via on-site facilities represented by the SUSTAIN rain barrel BMP. These residential on-site detention facilities can range from a standard commercially available rain barrel to larger custom and/or commercially available storage tanks that would provide greater storage capacity, albeit at greater cost, but would conceptually be more cost-effective assuming a lower cost per unit area of rooftop treated. The overflow from the on-site detention facility would flow into a bioretention facility (i.e., rain garden). The bioretention facility would also receive runoff from other impervious surfaces on the residential property, which would primarily be driveways and patios. Rooftop runoff from commercial/industrial development would be treated using bioretention facilities and parking areas associated with commercial/industrial development would be converted to porous pavement. Untreated surface runoff and under drain flow from the porous pavement would be routed to the bioretention treatment facilities. Road runoff would be treated using roadside bioretention facilities.

Runoff from pervious HRUs associated with residential and commercial/industrial land use (e.g., disturbed grass and forest) was routed to the outlet without treatment, although scenarios were explored in which a portion of the pervious runoff was treated using bioretention and/or detention facilities. Although there are no agricultural lands present in the pilot study area, there are agricultural lands in the Newaukum Creek basin. These lands are considered to be pervious HRUs and therefore only generate surface runoff during larger rainfall events where the rainfall rate exceeds the infiltration capacity of the soil. This runoff would be routed to and treated by bioretention facilities.

[9] Detention ponds for this project are "stacked" ponds with a wet pond (standing water) with runoff storage available above the wet pond (often referred to as a dry pond). These types of ponds are used for water quantity and water quality treatment.

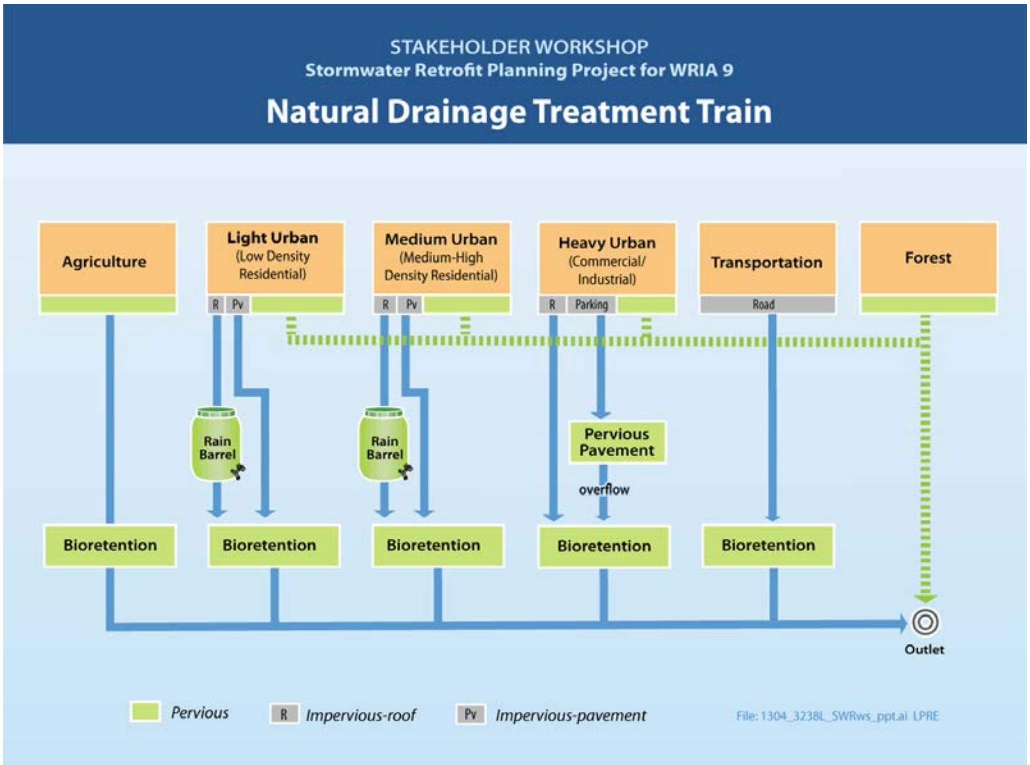

Figure 4. Natural Drainage Treatment Train.

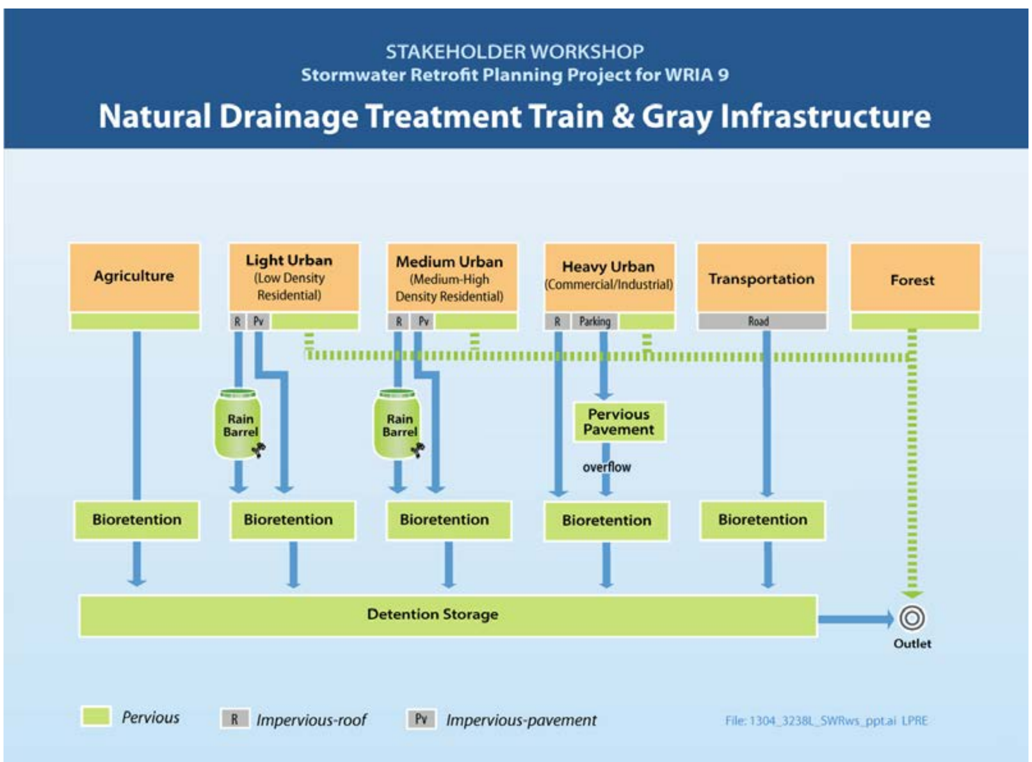

Figure 5. Natural Drainage and Gray Infrastructure Treatment Train.

2.2 BMP Design Assumptions

Stormwater BMP designs and associated unit costs for use in SUSTAIN were developed by a technical workgroup formed for this purpose.[10] Unit BMP cost assumptions are described in the next section (Section 2.3).

BMP designs were tailored to provide inputs to the SUSTAIN model and as with many modeling exercises require simplification of as-built designs to match the complexity allowed within the model. The design goals and general concepts are described for each BMP type below. The detailed SUTAIN model inputs required to implement these designs are provided in Table 2.

2.2.1 Residential On-site Detention Facilities

Two types of residential on-site detention BMPs were designed for use in SUSTAIN modeling scenarios. Conceptually, these BMPs detain residential rooftop runoff, but they provide no water quality benefit. One design represents a standard 55 gallon rain barrel. The second design represents a much larger receptacle that would best be described as a custom on-site detention facility or cistern. Of note, the cistern design for use in SUSTAIN does not include any indoor water use; rather the stored water is for outdoor use.

The residential rain barrel design is a cylinder that is 1.9 ft in diameter and 2.6 ft in height ((1.9/2)^2 x π x 2.6 = 7.37 ft3; 7.37 x 7.48052 = 55.1 gal). To prevent overflow from the rain barrel being limited by the weir, overflow to the rain garden occurs over a rectangular weir with a weir crest width set to 5 ft. The orifice is at the bottom of the barrel and has a diameter of 5/8" (0.625 in) to represent a standard hose fitting. The number of dry days required before water is released via gravity through the orifice is 1 day (i.e., 24 hours without any inflow to the barrel). The first-order pollutant decay rate was set to zero so no TSS removal occurs in the barrel.

The custom on-site detention BMP is 10 ft in diameter and 5 ft in height ((10/2)^2 x π x 5 = 392.7 ft^3; 392.7 x 7.48052 = 2,937.6 gal). Overflow to the rain garden occurs over a rectangular weir with a weir crest width of 5 ft so overflow from the facility is not limited by the weir. The orifice is at the bottom of the custom detention facility and has a diameter of 5/8" (0.625 in). The number of dry days required before water is released through the orifice is 1 day. The first-order pollutant decay rate was set to zero so no TSS removal occurs.

2.2.2 Bioretention Facilities

Two types of bioretention facilities were considered in this study. One type represents a residential BMP characterized as a rain garden. The second type of facility represents a bioretention BMP that treats runoff from public roads. Depending on the dominant

[10] The technical workgroup consisted of King County staff (Jeff Burkey, Curtis DeGasperi, Mark Wilgus), Dr. Rich Horner (University of Washington) and Ben Parrish (City of Covington) and the workgroup was facilitated by Tamie Kellog (Kellog Consulting).

underlying soil type in a particular model catchment, either facility may or may not have an underdrain. In catchments underlain predominantly by very poorly drained soils (Type D soils), the facility will include an underdrain that will capture all of the infiltrated water. In all other areas, no underdrain will be included in the design. About half of the NEW151 catchment contains poorly drained Type D soils (Figure 7). Model scenarios with and without underdrains (assuming till soils) are evaluated in this pilot study.

A unit of bioretention was represented by a 100-ft^2 area with a 1.5-ft layer of bioretention soil with a porosity of 0.4 (40%) and a 1-ft ponding depth.[11] Infiltration rates to native till and outwash soils (no underdrain) were set to 0.3 and 2.0 in/hr, respectively, to represent long-term percolation rates in these soils. In areas with very poorly drained Type D soils, bioretention facilities will include an underdrain (i.e., no infiltration to native soils) that will release water to the outlet of the catchment or to the detention pond in the Green + Gray BMP scenario. Since about half of the pilot study catchment contains poorly drained Type D soils, scenarios with and without underdrains were evaluated in this pilot study.

First-order TSS decay rates to simulate TSS removal in BMPs were selected based on analyses conducted by Herrera in their development of SUSTAIN models to evaluate cost-effective pollutant treatment approaches in an urbanized basin in Federal Way, WA (Herrera 2013). A 1st order TSS decay rate of 0.02/hr was chosen to simulate TSS removal in the bioretention cell. When an underdrain was incorporated, a removal fraction of 0.08 was used to represent TSS removal in the underdrain. Note that water that infiltrates to native soil (i.e., does not overflow or exit through the underdrain when present) results in removal of associated TSS.

Evapotranspiration loss from these facilities is included in the SUSTAIN model as an annually repeating monthly average potential evapotranspiration rate derived from the long-term (Oct 1948-Sep 2009) daily rates used in the HSPF model. The monthly rates specified in the model are shown in Figure 6.

2.2.3 Porous Commercial Parking Areas

Porous pavement (consisting of concrete or asphalt) was considered in this study and represents replacement of impervious parking areas on commercial developments with porous pavement. Depending on the underlying soil type, the porous pavement may or may not have an underdrain. In areas underlain by very poorly drained soils (Type D soils), the porous pavement will include an underdrain that will capture all of the infiltrated water. In all other areas, no underdrain will be included in the design. Since about half of the pilot study catchment contains poorly drained Type D soils, scenarios with and without underdrains were evaluated in this pilot study. In either case, surface overflow under saturated pavement conditions is directed to a rain garden (see above) and when an underdrain is present, flow from the underdrain is also routed to the rain garden.

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[11] The maximum ponding depth of 1 foot is based on expected revisions to the King County Surface Water Drainage Manual, which will require a Vb/Vr ratio of 3 (The ratio of the facility storage volume Vb to the volume of runoff from the mean annual storm Vr, where Vr = mean annual storm depth x runoff coefficient).

A unit of porous pavement was represented by a 100-ft^2 area with a 1.6-ft layer of porous surfacing material and engineered subsurface aggregate layers with an average porosity of 0.3 (30%) and a 0.01-in depression storage depth. This is essentially the same design as used in the Federal Way SUSTAIN case study (Herrera 2013) and is a necessary generalization for simulating porous pavement BMPs in SUSTAIN. Details of the porous pavement design are provided in Appendix A. Infiltration rates to native till and outwash soils (no underdrain) were set to 0.3 and 2.0 in/hr, respectively, to represent long-term percolation rates in these soils.

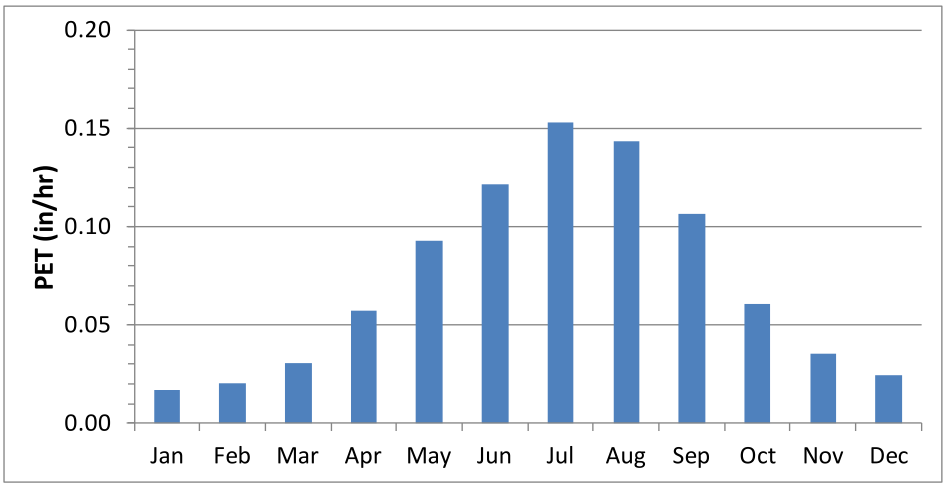

Figure 6. Bar chart showing monthly varying potential evapotranspiration (PET) specified for bioretention facilities.

Note: Monthly average PET derived from the long-term (1949-2009) input to the Newaukum HSPF model.

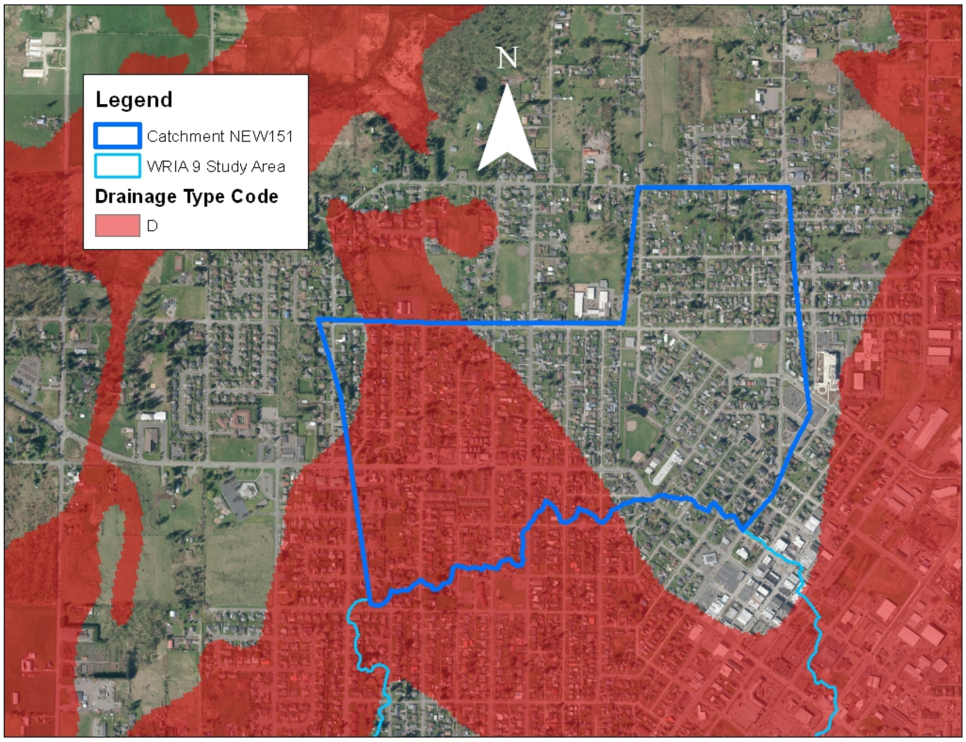

Figure 7. Map showing location of poorly drained Type D soils in the Newaukum pilot study catchment (NEW151).

Source: Gridded Soil Survey Geographic (gSSURGO) Database: http://soils.usda.gov/survey/geography/ssurgo/description_gssurgo.html

First-order TSS decay rates to simulate TSS removal in BMPs were selected based on analyses conducted by Herrera (2013) in their development of SUSTAIN models to evaluate cost-effective pollutant treatment approaches in an urbanized basin in Federal Way, WA. It was assumed that no pollutant removal occurs as water infiltrates the porous pavement (i.e., 1st order TSS decay rate is zero). When an underdrain is present, a TSS removal fraction of 0.08 was used. Note that when no underdrain is present, water that infiltrates to native soil also results in the removal of TSS.

2.2.4 Detention Pond

Public stormwater detention facilities were considered in this pilot study to represent "gray" as opposed to the "green" or Natural Drainage Design (or LID) BMPs addressed above in the Natural Drainage Design Treatment Train. Detention ponds were designed using version 3.0 of the Western Washington Hydrology Model (WWHM3). Three separate pond designs were developed for treatment of 1-acre of runoff from three levels of development identified in the 2007 Land Use/Land Cover data used in the HSPF model set up for this project. These development categories in HSPF are described as 1)

Commercial/Industrial, 2) Medium to High Density Residential and 3) Low Density Residential. Conceptually, these ponds are sealed and no infiltration to native soils occurs.

For the treatment of 1 ac of runoff from Commercial/Industrial land, the unit pond length and width are 105 and 35 ft, respectively. The rectangular overflow weir is 5.2 ft above the pond bottom with a width of 4.4 ft and the 0.542-in diameter orifice is 1.2 ft above the pond bottom.

For the treatment of 1 ac of runoff from High/Medium Density Residential development, the unit pond length and width are 85 and 28 ft, respectively. The rectangular overflow weir is 5.4 ft above the pond bottom with a width of 4.4 ft and the 0.537-in diameter orifice is 1.4 ft above the pond bottom.

For the treatment of 1 ac of runoff from Low Density Residential development, the unit pond length and width are 71 and 24 ft, respectively. The rectangular overflow weir is 5.1 ft above the pond bottom with a width of 4.4 ft and the 0.547-in diameter orifice is 1.1 ft above the pond bottom.

First-order TSS decay rates to simulate TSS removal in BMPs were selected based on analyses conducted by Herrera (2013) in their development of SUSTAIN models to evaluate cost-effective pollutant treatment approaches in an urbanized basin in Federal Way, WA. A 1st order TSS decay rate of 0.02/hr was chosen to simulate TSS removal.

The monthly PET values described for the bioretention facilities above are also applied to the detention pond BMP.

Table 2. SUSTAIN BMP design details.

	Residential On-site Detention Facility		Bioretention		Porous Pavement		Detention Pond
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
Design Drainage Area a	0.01 ac	0.04 ac	0.0215 ac	0.0215 ac	100 ft^2	100 ft^2	1 ac
Infiltration Model (Green-Ampt, Horton, Holtan) [INFILTM]	NA	NA	2 (Holtan)	2 (Holtan)	2 (Holtan)	2 (Holtan)	NA
Pollutant Removal Method (1st Order Decay, K-C' method – Kadlec and Knight Method) [POLREMM]	0 (1st Order Decay)	0 (1st Order Decay)	0 (1st Order Decay)	0 (1st Order Decay)	0 (1st Order Decay)	0 (1st Order Decay)	0 (1st Order Decay)
Pollutant Routing Method (Completely Mixed, CSTRs in series) [POLROTM]	1 (Completely Mixed)	1 (Completely Mixed)	1 (Completely Mixed)	1 (Completely Mixed)	1 (Completely Mixed)	1 (Completely Mixed)	1 (Completely Mixed)

	Residential On-site Detention Facility		Bioretention		Porous Pavement		Detention Pond
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
Dimensions Tab							
Number of Units	Optimize	Optimize	Optimize	Optimize	Optimize	Optimize	Optimize
Diameter/Length (ft) **[LENGTH]**	1.9	10	10	10	10	10	105
Width (ft) **[WIDTH]**	NA	NA	10	10	10	10	35
Exit Type **[EXITTYPE]**	1	1	1	1	NA	NA	1
Orifice Diameter (in) **[DIAM]**	0.625	0.625	0	0	NA	NA	0.542
Orifice Height (Ho, ft) **[OHEIGHT]**	0	0	0	0	NA	NA	1.2
Release Type **[RELEASETYPE]**	2	2	NA	NA	NA	NA	3
Number of dry days **[DDAYS]**	1	1	NA	NA	NA	NA	NA
Number of People **[PEOPLE]**	NA	NA	NA	NA	NA	NA	NA

	Residential On-site Detention Facility		Bioretention		Porous Pavement		Detention Pond
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
Weir Type **[WEIRTYPE]**	1 (rectangular)	1 (rectangular)	1 (rectangular)	1 (rectangular)	1 (rectangular)	1 (rectangular)	1 (rectangular)
Weir Height (Hw, ft) **[WEIRH]**	2.6	5	1.0	1.0	0.01	0.01	5.2
Rectangular Weir Crest Width (B, ft) **[WEIRW]**	5	5	10	10	10	10	4.4
Triangular Weir Angle (theta, deg) **[THETA]**	NA	NA	NA	NA	NA	NA	NA
Substrate Properties Tab							
Depth of Soil (Ds, ft) **[SDEPTH]**	NA	NA	1.5	1.5	1.6	1.6	NA
Soil Porosity (0-1) **[POROSITY]**	NA	NA	0.4	0.4	0.3	0.3	NA
Soil Field Capacity **[FCAPACITY]**	NA	NA	0.244	0.244	NA	NA	NA
Soil Wilting Point **[WPOINT]**	NA	NA	0.136	0.136	NA	NA	NA
Initial Surface Water	NA	NA	0	0	0	0	NA

	Residential On-site Detention Facility		**Bioretention**		**Porous Pavement**		**Detention Pond**
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
Depth (ft) **[WATDEP_I]**							
Initial Moisture Content (0-1) **[THETA_I]**	NA	NA	0	0	0	0	NA
Saturated Soil Infiltration (in/hr) **[FINFILT]**	NA	NA	2.0 / 0.3	0	2.0 / 0.3	0	NA
ET Multiplier **[ET_MULT]**	NA	NA	1.0	1.0	0.0	0.0	1.0
Route Infiltration to Aquifer	NA	NA	Yes	NA	Yes	NA	NA
Consider Underdrain Structure **[UNDSWITCH]**	NA	NA	0 (No)	1 (Yes)	0 (No)	1 (Yes)	0 (No)
Storage Depth (Du, ft) **[UNDDEPTH]**	NA	NA	NA	0.5	NA	0.25	NA
Media Void Fraction (0-1) **[UNDVOID]**	NA	NA	NA	0.5	NA	0.35	NA
Background Infiltration	NA	NA	NA	0	NA	0	NA

	Residential On-site Detention Facility		Bioretention		Porous Pavement		Detention Pond
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
(in/hr) **[UNDINFILT]**							
Route Underdrain/Outlet to:	Bioretention	Bioretention	NA	Outlet/Pond	NA	Outlet/Pond	Outlet
Infiltration Parameters Tab							
Green-Amp Infiltration Parameters	NA	NA	NA	NA	NA	NA	NA
Suction Head (in) **[SUCTION]**	NA	NA	NA	NA	NA	NA	NA
Initial Deficit (fraction) **[IMDMAX]**	NA	NA	NA	NA	NA	NA	NA
Horton Infiltration Parameters							
Maximum Infiltration (in/hr) **[MAXINFILT]**	NA	NA	NA	NA	NA	NA	NA
Decay Constant (1/hr)	NA	NA	NA	NA	NA	NA	NA

	Residential On-site Detention Facility		**Bioretention**		**Porous Pavement**		**Detention Pond**
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
[DECAYCONS]							
Drying Time (day) **[DRYTIME]**	NA	NA	NA	NA	NA	NA	NA
Maximum Volume (in) **[MAXVOLUME]**	NA	NA	NA	NA	NA	NA	NA
Holtan Infiltration Parameters							
Vegetative Parameter A **[AVEG]**	NA	NA	1	1	1	1	NA
Monthly Growth Index **[GIi]**	NA	NA	1	1	1	1	NA
Water Quality Parameters Tab (for TSS)							
Decay factor (1/hr) **[QUALDECAY1]**	0	0	0.02	0.02	0.0	0.0	0.02
K (ft/yr) **[QUALK1]**	NA	NA	NA	NA	NA	NA	NA
C* (mg/L) **[QUALC*1]**	NA	NA	NA	NA	NA	NA	NA

	Residential On-site Detention Facility		Bioretention		Porous Pavement		Detention Pond
	Rain Barrel	**Custom design**	**Outwash / Till**	**D Soils**	**Outwash / Till**	**D Soils**	**(e.g., Urban High)**
Design Unit Size	7.37 ft^3 (55 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2	100 ft^2	19,110 ft^3
Underdrain Removal Rate (fraction, 0-1) **[QUALPCTREM1]**	NA	NA	NA	0.08	NA	0.08	NA

NA = Not applicable.

a The design drainage area is a conceptual starting point used to estimate an upper limit on the number of each BMP type to use in cost-effectiveness optimization model runs. Initial optimization model results can then be used to refine the range and number of intervals to use in final cost-effectiveness optimization runs.

2.3 BMP Cost Assumptions

Unit BMP costs for use in SUSTAIN were estimated using costs summarized from the Puget Sound Stormwater BMP Cost Database (Herrera 2011), additional sources of information and the expertise of a technical workgroup formed for the purpose of developing Best Management Practice (BMP) designs and design unit costs.[12] The intent is to use the designs and unit cost estimates in BMP optimization scenarios to identify cost effective BMP treatments that will reduce stream flashiness and reduce sediment and associated contaminant loading.

Another objective of the BMP modeling effort is to parse the total cost of any particular BMP scenario into public and private costs. The costs used in the SUSTAIN cost-effectiveness optimizations and the approach to distinguishing between costs to the public and private sector are described below.

Unit cost estimates were developed based on available information on the costs of 1) design and permitting, 2) construction (including materials), 3) annual operation and maintenance (O&M) costs and 4) inspection and enforcement (I&E) costs when applicable. The unit cost estimate for storm water ponds also included an estimate of land cost per unit pond assuming that retrofit construction of storm water ponds will require the public acquisition of private property. Details regarding the development of I&E costs, including inspection and enforcement frequency for BMPs are provided in Appendix B. The total Present Value (PV) unit cost of a particular BMP was determined using a discount rate of 5% and a 30-year O&M/I&E period following the approach described by Pomeroy and Houdeshel (2009). No replacement costs were assumed during the life of the 30 year planning period.

Private costs were assumed to be equal to the cost of all BMPs developed on private property, which includes on-site detention facilities such as rain barrels or custom on-site detention facilities, bioretention (i.e., rain gardens) and conversion of commercial parking lots to porous pavement. Public costs are associated with bioretention facilities that treat road runoff and detention ponds and I&E costs.

2.3.1 Residential On-site Detention Facilities

Rain barrel unit costs summarized from the Puget Sound Stormwater BMP Cost Database (Puget Sound Database, Herrera 2011) ranged from $24.50 to $349.00 and averaged $168.65. Costs were also summarized for connection of the rain barrel to the gutter system, which ranged from $2.50 to $30.00 and averaged $23.17. Installation costs ranged from $21.23 to $29.00 and averaged $25.12. No O&M costs were provided and assumed to be negligible because rain barrels would not be subject to the maintenance demands of treatment facilities such as sediment removal or vegetation management. Using the

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[12] The technical workgroup consisted of King County staff (Jeff Burkey, Curtis DeGasperi, Mark Wilgus), Dr. Rich Horner (University of Washington) and Ben Parrish (City of Covington) and the workgroup was facilitated by Tamie Kellog (Kellog Consulting). Additional sources of information are referenced as appropriate below.

average costs for materials and labor results in a total construction cost of $216.94 per unit.

Cistern costs per cubic foot summarized from the Puget Sound Database (Herrera 2011) are most relevant to estimating the cost of a custom on-site detention facility for this study and ranged from $2.00 to $45.00 per ft^3 and averaged $12.54 per ft^3. This suggests a cost of the approximately 3,000 gal (400 ft^3) on-site detention facility proposed for evaluation in this study that would range from $800 to $18,000 and average approximately $5,000. This average cost appeared high to the members of the technical workgroup developing cost estimates, especially considering the wide range of costs found in the Puget Sound Database. The lowest unit cost in the database was for an 81,000 gallon cistern, while costs for cisterns in the 3,000 gallon size range were $3, $4 and $11 per ft^3. Using the middle cost estimate of $4 per ft^3 results in a unit cost of $1,600 for a 3,000 gallon custom residential on-site detention facility.

Construction costs selected for use in SUSTAIN were $220 unit cost for a rain barrel and $1,600 unit cost for a custom residential on-site detention facility. These costs conceptually represent round figures for cost of materials and construction, including the cost of labor to construct or install the systems. O&M costs are considered to be negligible. However, it is presumed that these facilities would require inspection every five years by a public inspector and a 15% frequency of enforcement actions for private facilities resulting in an annual per unit I&E cost of $85.40. The total PV cost then becomes $1,533 and $2,913 for a rain barrel and custom cistern, respectively. Construction costs are private costs and I&E costs are public. Conceptually, these facilities will be constructed on available private land and will not require the purchase of additional land. Proposed total PV unit cost of the two residential on-site detention BMPs and associated cost details are presented in Table 3.

2.3.2 Bioretention Facilities

Bioretention project cost information summarized from the Puget Sound Database (Herrera 2011) ranged from $1.13 to $86.16 and averaged $30.55 per ft^2, while design costs ranged from $0.52 to $54.13 and averaged $16.08 per ft^2. Annual O&M costs ranged from $0.19 to $2.68 and averaged $1.22 per ft^2.

Proposed bioretention (rain garden) costs for use in SUSTAIN as part of a parallel project to evaluate BMP treatment cost effectiveness in a Federal Way, WA drainage basin are $35.00 per ft^2 for construction, $8.75 per ft^2 for design (25% of construction cost) and a $40.04 PV (30-yr lifecycle) O&M cost (Herrera 2013). A scaling factor of 2.5 was applied to the total PV cost (including the O&M cost) to account for a larger footprint of an as-built version of the 4.1 ft x 4.1 ft rain garden BMP modeled in SUSTAIN (Herrera 2013).[13] This resulted in a PV cost of $206.42 per ft^2.

[13] This is due to the simplification in SUSTAIN that assumes that BMPs have vertical side walls rather than sloped sides as would be typical of as-built BMPs.

A recently completed stormwater retrofit study for the Juanita Creek basin (King County 2012), used cost information develop as part of Seattle's RainWise program, which provided a construction cost estimate of $20 per ft^2.

This pilot study used a construction cost of $20 per ft^2, which implies that a 100 ft^2 (10x10 ft) rain garden (or 100 ft^2 unit of road runoff bioretention BMP) costs $2,000 to build and $1,691 (O&M = $1.10 ft^{-2} yr^{-1}) to maintain over a 30-year period assuming a discount rate of 5%. Adding in the cost of I&E for private rain garden facilities and inspection only for public roadside bioretention resulted in total PV costs of $69.73 and $63.04 per ft^2 for rain gardens and roadside bioretention facilities, respectively. These PV costs are used in the SUSTAIN model assuming that private land is available at no additional cost for rain gardens and that public right of way is available at no additional cost for road bioretention facilities. Total PV unit cost of the bioretention BMPs and associated cost details are presented in Table 3.

2.3.3 Porous Commercial Parking Areas

Herrera (2011) reported an average of $13.90per ft^2 for construction (usually, including design) of porous concrete and asphalt systems, working from the Puget Sound Database. A single source reported an annual O&M cost of $0.02per ft^2. These costs are not out of line with those reported in a survey of other sources.[14]

Herrera (2013) identified construction costs for porous asphalt as $20per ft^2 on outwash soil and $19 per ft^2 on till for use in the Federal Way SUSTAIN study. The additional cost on outwash soil was associated with the cost of a treatment liner required to protect groundwater quality. Herrera (2013) also specified the cost of design (20% of construction costs) and an annual O&M cost of $0.05 per ft^2. The total PV cost on till and outwash soils used by Herrera (2013) in their SUSTAIN study was $26.75 and $25.55 per ft^2, respectively. Herrera (2013) did not explicitly include I&E costs.

This pilot study used a $20 per ft^2 construction and $0.02 per ft^2 O&M cost to develop the SUSTAIN porous pavement total cost input. It was assumed that the design cost is included in the estimated construction cost. An I&E cost per 100 ft^2 unit of porous pavement was developed, which resulted in an estimated annual I&E cost of $427.00. These costs result in a total PV cost of $85.95 per ft^2 of porous pavement over a 30-year period assuming a discount rate of 5%. These are the costs used in this SUSTAIN pilot study and assume that conversion of impervious commercial parking areas is a private expense and I&E costs are a public expense. Proposed total PV unit cost of the porous pavement BMP and associated cost details are presented in Table 3.

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[14] http://www.crwa.org/projects/bmpfactsheets/crwa_permeable_pavement.pdf
http://www.projectcleanwater.org/pdf/lid/Permeable_Pavements.pdf
http://ntl.bts.gov/lib/43000/43500/43570/TSR-2011-permeable-pavements.pdf
www.region9wv.com/Bay/Calculators/Permeable_Pavement.xls
http://www.saveitlancaster.com/wp-content/uploads/2011/10/07_PorousPavement.pdf
www.lowimpactdevelopment.org/.../3-2_permeablepavement_draft.doc

Table 3. Cost Assumptions for Low Impact Development BMPs (30-yr planning horizon with 5% discount rate).

	Residential On-site Detention Facility		Bioretention		Porous Pavement
	Rain Barrel	Custom design	Rain Garden	Roadside [a]	
Design Unit Size	6.75 ft^3 (50 gal)	393 ft^3 (2,938 gal)	100 ft^2	100 ft^2	100 ft^2
Total Present Value	$ 1,533 /unit	$ 2,913 /unit	$ 69.73 /ft^2	$ 63.04 /ft^2	$85.95 / ft^2
Inspections/Enforcement [a]	$ 85.40 /yr	$ 85.40 /yr	$ 213.50 /yr	$ 170.00 /yr	$ 427.00 /yr
Design and Permitting Cost	~$0 [b]	~$0 [b]	c	c	c
Construction Cost	$ 220/unit	$ 1,600 /unit	$ 20 /ft^2	$ 20 /ft^2	$20 /$ft^2$
Annual Operation and Maintenance Cost	NA	NA	$ 1.10 /ft^2	$ 1.10 /ft^2	$0.02 /$ft^2$
Land Cost	NA	NA	NA	NA	NA

NA = Not applicable.

[a] I&E is a public cost and construction and O&M costs for roadside bioretention are public costs. All other costs assigned to private land owners. See Appendix B for I&E details

[b] Assumed to be negligible.

[c] Conceptually included in construction cost

2.3.4 Detention Pond

We propose to consider three detention pond designs for use in different areas depending on the predominant level of development (i.e., Commercial/Industrial, High/Medium Density Residential, and Low Density Residential – High, Medium, and Low Development) identified in the 2007 GIS land cover data (Alberti, M, University of Washington Urban Ecology Research Laboratory) used to develop the HSPF models for this project. Land costs for each facility type were estimated by averaging the current assessed value of land for each of the three land cover types across the overall project study area. Transaction costs (e.g., commissions, title transfer) were not explicitly considered and were assumed to account for a small amount of the total cost relative to the appraised value of the land and associated improvements. All detention pond costs, including land costs are assumed to be public costs.

Detention pond construction costs per cubic foot summarized from the Puget Sound Database are most relevant to estimating the cost of wet ponds for this study and ranged from \$1.22 to \$39.41 per ft^3 and averaged \$7.97 per ft^3. Only one design and one O&M cost were reported – \$0.61 and \$0.03 per ft^3.

Detention pond costs for use in SUSTAIN as part of the Federal Way SUSTAIN study were \$10.00 per ft^2 for construction (Herrera 2013). Herrera (2013) used a design cost of 10 percent of the construction cost and an O&M cost of \$0.35 per ft^2 that would occur twice over a 30-yr lifecycle. The property acquisition cost was assumed to be \$4.00 per ft^2. The total PV cost over a 30-yr planning horizon was given as \$24.70 per ft^2, including the cost of land.

The detention pond costs used in this pilot study are similar to those used by Herrera (2013), although the comparison is complicated because the costs for this pilot study were developed on a unit volume rather than unit area basis; except for land costs. Including the O&M cost and a 30-year planning period with a 5% discount rate results in a total cost estimate for detention pond design, construction and O&M of \$4.78 per ft^3 (Table 4). Using the design unit areas and volumes provided in Table 4 allows the cost per ft^3 to be converted to cost per ft^2 for comparison with the Herrera (2013) study, which results in a total PV unit area cost of \$25.81 per ft^2. Land costs will be input separately into SUSTAIN as the present value cost per ft^2 of land depending on the predominant land use type (and associated detention pond treatment design) in a particular basin. For example, in this pilot study the predominant land use is High/Medium Density Residential so the total present value unit cost for one unit of detention would be \$44.06 per ft^2 or \$104,863 per pond unit.

Although the land costs in SUSTAIN only account for the surface area of the pond, no consideration has been made to adjust the land costs to account for necessary buffer areas around the ponds. Herrera (2013) did not apply a scaling factor to their pond cost estimates for use in SUSTAIN. In general, unit ponds as modeled in SUSTAIN using the aggregate BMP approach are conceptual and in reality several unit ponds might be aggregated and placed at a single site, which would affect assumptions made about necessary buffer areas and associated scaling factors.

Table 4. Assumptions for detention ponds (30-yr planning horizon with 5% discount rate).

	Detention Pond		
	Commercial /Industrial	High/Medium Density Residential	Low Density Residential
Design Unit Volume	19,110 ft^3	12,852 ft^3	8,690 ft^3
Design Unit Area	3,539 ft^2	2,380 ft^2	1,704 ft^2
Total Present Value (Design, Construction and O&M)	\$25.81 /ft^2 (\$4.78 /ft^3)	\$25.81 /ft^2 (\$4.78 /ft^3)	\$25.81 /ft^2 (\$4.78 /ft^3)
Design and Permitting Cost	\$ 1.20 /ft^3	\$ 1.20 /ft^3	\$ 1.20 /ft^3
Construction Cost	\$ 3.43 /ft^3	\$ 3.43 /ft^3	\$ 3.43 /ft^3
Annual Operation and Maintenance Cost	\$ 0.01 /ft^3	\$ 0.01 /ft^3	\$ 0.01 /ft^3
Land Cost [a]	\$ 23.00 /ft^2	\$ 18.25 /ft^2	\$ 6.50 /ft^2

NA = Not applicable or assumed to be negligible.

[a] Land costs for wet ponds will vary depending on predominant level of development in basin, which is highly correlated with average land cost. There are three development level categories and three associated land costs.

2.4 Estimation of Residential Rooftop, Commercial Parking and Road Surface Areas

The HSPF models developed for this project explicitly model the runoff from roads do not separately model the runoff from EIA associated with rooftops and paved areas within residential and commercial land uses. The road EIA from the HSPF model (and the associated HRU time series file) was used as the area to be treated via roadside bioretention in the pilot study SUSTAIN model.

Because the HSPF model does not explicitly model runoff from residential roofs or commercial parking areas, a method was developed to estimate the contributing area of these particular surfaces within the study catchment. Although digitizing these features from high resolution orthophotos would be feasible on the scale of this pilot study catchment, this would not be feasible to do at a larger scale or for a large number of additional catchments. The selected method relies on readily available county-wide GIS data that allows for the extension of the method to the entire study area if necessary and was based on an initial effort conducted by Gardner et al. (2012).

The method uses a county-wide 6-ft resolution grid of lidar-derived heights of man-made features (i.e., impervious cover) (Figure 8).[15] Grid cells classified as impervious based on a 2009 multi-source interpretation of impervious/impacted surfaces[16] were assigned a height above ground based on the difference between the digital surface and ground models derived from county-wide lidar data referenced above. The man-made feature height grid was intersected with the grid used to develop the HSPF HRUs (Figure 9).[17] The area of man-made features above and below a 6-ft height threshold was used to quantify the rooftop area and remaining impervious area for each type of HRU in the catchment. A 6-ft threshold was chosen based on previous experience with height models derived from the county-wide lidar data, which tend to be less accurate for the ground surface due to the confounding influence of vegetation.[18]

The fraction of the total impervious area above 6 ft within residential HRUs was used to calculate the portion of the HSPF residential EIA area that was routed to the on-site detention system in SUSTAIN. The fraction of the total impervious area below 6 ft within the commercial HRUs was used to calculate the portion of the HSPF commercial EIA area that could be converted to porous parking area.

[15] King County. 2010. Man Made Features Area and Height. (http://www5.kingcounty.gov/sdc/raster/landcover/ManmadeFeatureElevationMetadata.html)

[16] King County. 2011. 2009 Impervious and Impacted Surface of King County, Washington. (http://www5.kingcounty.gov/sdc/raster/landcover/Landcover2009ImperviousMetadata.html)

[17] This grid precedes the last step in the creation of the "lumped" HRU types/areas that become inputs to the HSPF model. The last step uses estimates of EIA associated with each gridded HRU type to estimate the area within the catchment represented by EIA (road, two residential density levels, and commercial EIA) and pervious HRUs, which is the remainder of the area of the gridded HRU types.

[18] The county lidar flights were flown during seasonal leaf-off periods, but twiggy ground vegetation confounded ground elevation estimates in some areas.

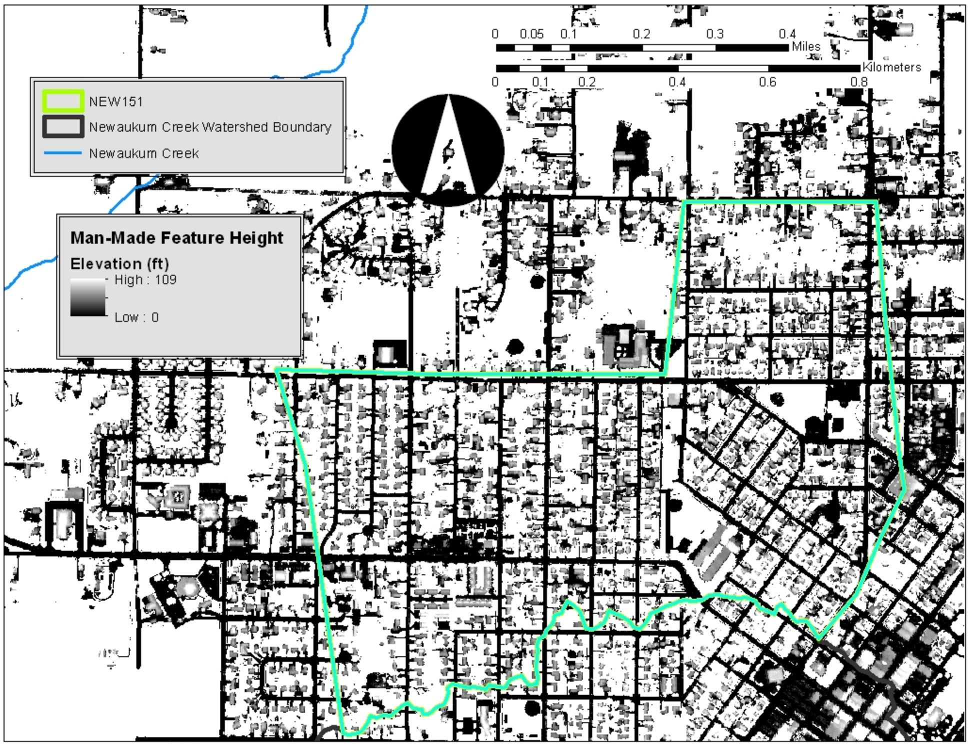

Figure 8. Map showing the man-made feature height grid over the pilot study catchment.

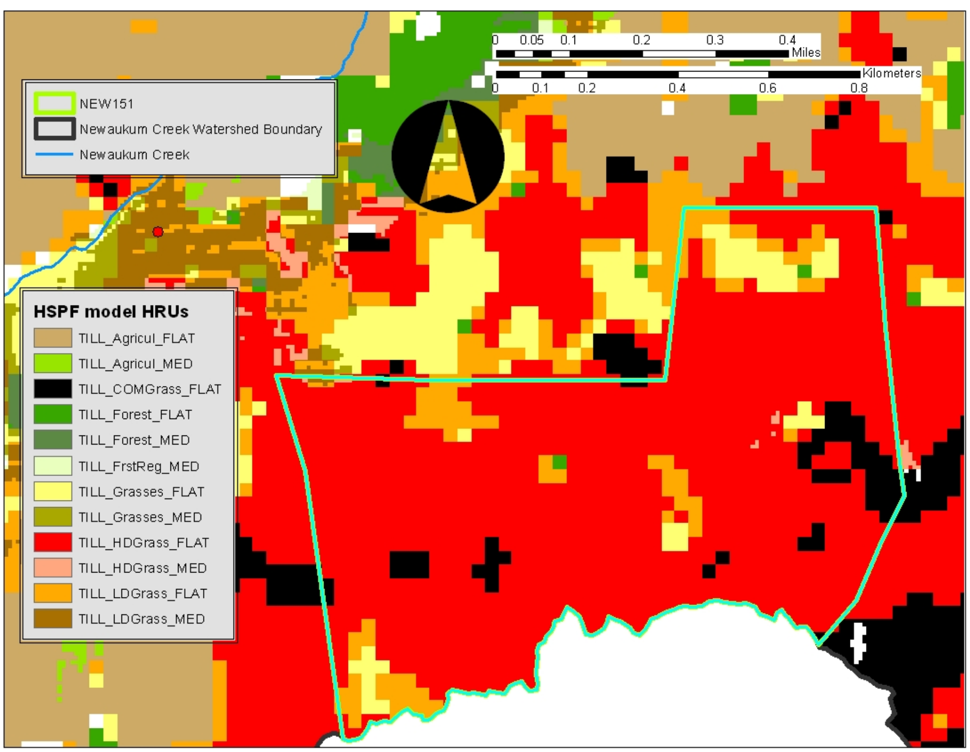

Figure 9. Map showing the HSPF Hydrologic Response Unit grid over the pilot study catchment.

2.5 Application of SUSTAIN Aquifer Component

SUSTAIN version 1.2 provides for the routing of BMP infiltration and pervious subsurface flow (pervious HRU interflow and active groundwater flow from the HSPF model) to aquifer storage reservoirs where it can be treated as infinite storage or released back to the stream network at a rate specified by a recession coefficient.[19] If treatment scenarios focused only on the treatment of runoff from EIA, use of the aquifer component would probably not be necessary. However, in scenarios involving treatment of surface runoff generated from disturbed pervious HRUs associated with development the use of aquifer storage is necessary. This is because without aquifer storage (and immediate release), the pervious subsurface flow would not be routed to the downstream assessment point. This lack of routing of subsurface flow to the downstream assessment point would be counted as completely treated without passing through any BMP. Immediate routing of pervious subsurface flow to the downstream assessment point is consistent with the routing of this flow at the catchment level in the HSPF model, which already accounts for delayed release from shallow and deep aquifer storage.

A second aquifer can be specified to capture the infiltration from bioretention facilities and porous parking areas. This aquifer can then be treated as infinite storage, giving the greatest credit to BMP effectiveness, or released at a slower rate that would provide less volume reduction benefit, but still providing some peak reduction benefit. A conceptual representation of the SUSTAIN aquifer routing scheme is provided in Figure 10.

[19] Groundwater discharge G(t) and deep seepage D(t) from aquifer storage S(t) at time t are calculated as G(t) = RC x S(t) and D(t) = SC x S(t) where RC and SC are aquifer recession and seepage constants (1/hr), respectively.

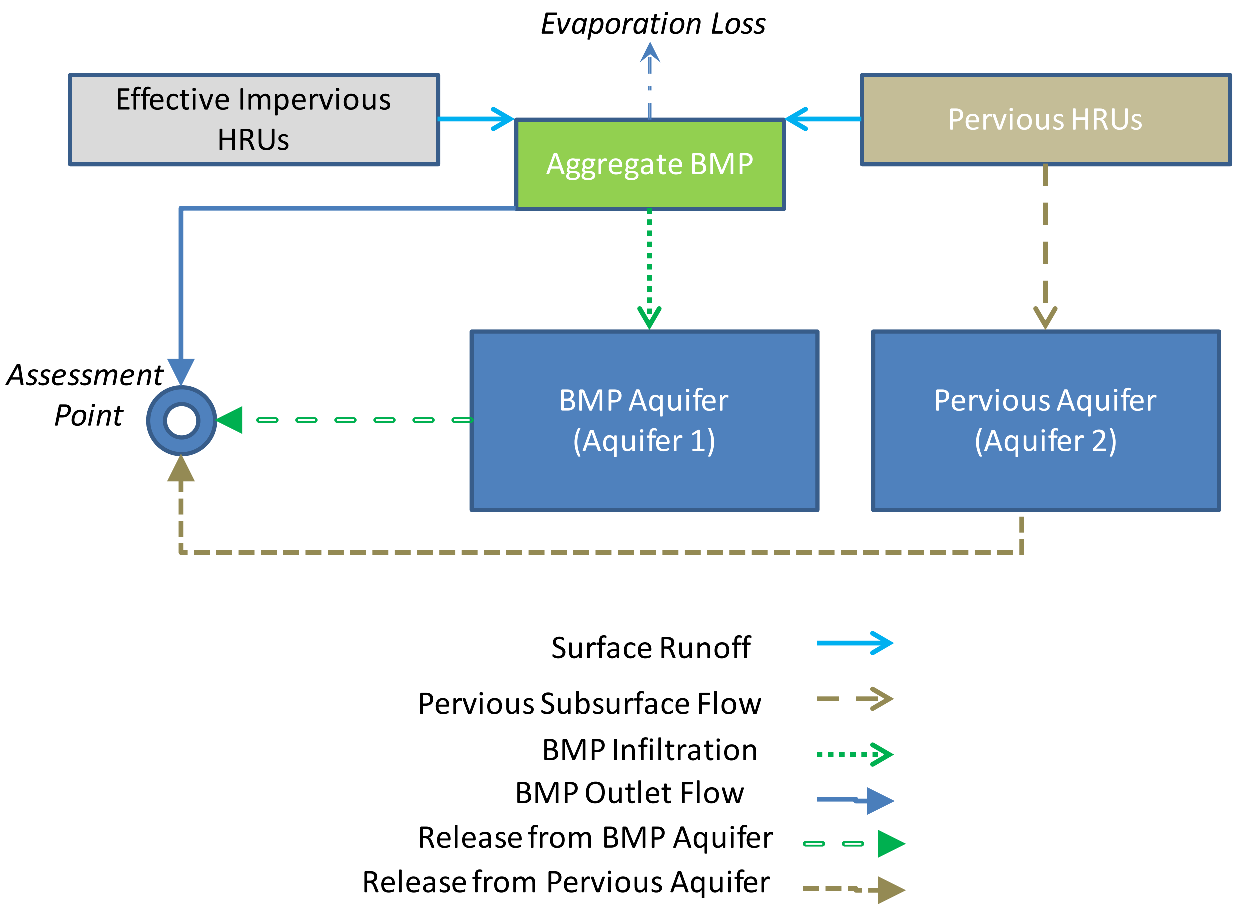

Figure 10. Schematic illustrating the aquifer routing scheme used in the SUSTAIN pilot study models.

2.6 Optimization Target

Two optimization options are available in SUSTAIN – 1) Scatter Search and 2) Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (U.S. EPA et al. 2009, Lee et al. 2012). The Scatter Search option is used to identify the number and/or sizes of BMPs needed to meet a target objective at minimum cost. The NSGA-II optimization option is used to develop a set of optimal solutions over a range of levels of effectiveness (i.e., cost-effectiveness curves). Because the focus of this study is on flow, rather than water quality control, and the cost-effectiveness curve provides for the exploration of the cost to meet a wide range of flow management (and by extension biological) goals, the NSGA-II optimization option was selected for use in this study.

There are a number of options for performing a cost-effectiveness analysis based on flow including minimizing the cost of reducing 1) annual average flow volume, 2) peak discharge, and 2) the frequency flow exceeds a specified flow threshold. The last option is consistent with one of the three hydrologic metrics chosen for use in this study – High

Pulse Count or HPC (Horner 2013). HPC is defined as the number of times the daily mean flow exceeded a high pulse flow threshold set as twice the long-term mean annual flow.[20]

The objective in the optimization is to reduce the number of HPCs observed under current conditions (Figure 11) to numbers that are more typical of the pre-development forested condition (Figure 12). HPC (and a number of other hydrologic metrics commonly called "flashiness" metrics) has shown a correlation with the benthic index of biological integrity (B-IBI) in King County streams (DeGasperi et al. 2009, Horner 2013), so it is hypothesized that reductions in flow flashiness will result in improvement in the biological integrity of local streams as represented by B-IBI scores.

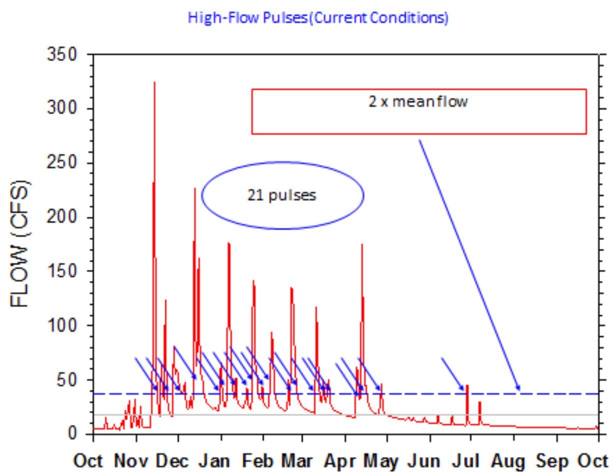

Figure 11. Hypothetical hydrograph illustrating the number of high pulse counts under current catchment conditions.

[20] The other two hydrologic metrics selected were High Pulse Range (HPR) defined as the range in days between the start of the first high flow pulse and the end of the last high flow pulse during a water year and 2-Yr Peak:Winter Base flow ratio (PEAK:BASE) defined as the ratio of the peak flow rate with a 2-yr return frequency to the mean base flow rate during the period October 1 through April 30.

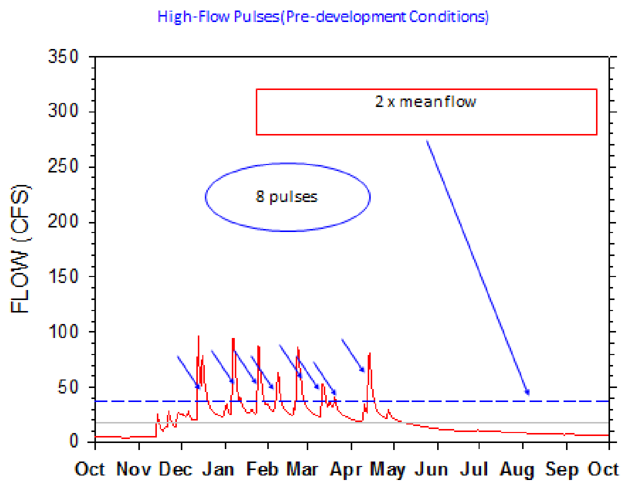

Figure 12. Hypothetical hydrograph illustrating the number of high pulse counts under pre-development forested catchment conditions.

In addition to the selection of an optimization target, a range from zero to an upper limit on the possible number of units of each BMP treatment type and the step increment from zero to the maximum possible number of BMPs of each type must be specified. The number of BMP types to optimize and the number of steps selected for an optimization run affect the number of possible BMP type and number permutations and hence the number of scenario iterations needed to generate a relatively smooth cost-effectiveness curve. The number of possible BMP types was determined based on the design treatment drainage area for each BMP (see section 2.2 above) with 20 equal steps from zero to the maximum number of BMPs. Table 5 shows the range and step size of the number of units of each BMP considered in the cost-effectiveness optimization runs.

A maximum number of model scenarios must also be specified. The SUSTAIN model runs conducted for this pilot study were based on a maximum of 1,000 scenario model runs. This was based on initial model testing using 700 to 2,000 model runs, which suggested that 1,000 model runs would generally be sufficient to generate a reasonably smooth cost-effectiveness curve.

2.7 Scenarios

As described above, two fundamentally different stormwater treatment approaches were evaluated as part of this pilot study: 1) Green and 2) Green + Gray. However, as can be seen from the large number of choices that must be made to set up and run a single SUSTAIN model, a number of scenarios based on the two fundamental treatment approaches were explored in this pilot study.

Table 5. Summary of the range and steps of the number of units of each BMP specified in the SUSTAIN cost-effectiveness model runs.

BMP Type	Number of Units		
	From	To	Step
Rain Barrel	0	2400	120
Cistern	0	600	30
Rain Garden [a]	0	500 (7200) [a]	25 (360) [a]
Porous Parking	0	1800	90
Roadside Bioretention	0	600	30
Detention Pond [b]	0	200	10

[a] *The number of rain garden units varied depending on whether or not surface runoff from pervious areas were treated. Numbers in parentheses are the number of units specified for scenarios in which 80 percent of the pervious area was treated.*

[b] *Range and steps for Green + Gray scenarios only.*

One set of scenarios explores the potential cost-effectiveness of custom on-site detention facilities (referred to as cisterns in this document) that are larger (albeit more expensive) than conventional rain barrels to the cost-effectiveness of more conventional rain barrels. Although the custom onsite detention facilities cost more per unit, they are assumed here to have a lower cost per unit area treated.

Another combination of scenarios explores the influence of directing a portion of surface runoff from disturbed pervious areas to the rain garden BMP on cost-effectiveness optimization results. The alternative model runs for this scenario are that all of the residential and commercial EIA is directed to bioretention treatment and none of the pervious area surface runoff is treated, or all EIA plus 80 percent of the residential and commercial pervious area surface runoff is directed to bioretention treatment. This combination of scenarios was motivated by the finding in the Juanita Creek Stormwater Retrofit Study that treatment of runoff from additional runoff generating areas beyond that from EIA was needed to best restore hydrologic conditions (King County 2012).

The third combination looks at the effect of the BMP aquifer recession coefficient on optimization results. Two different aquifer recession coefficients are tested; in one scenario the BMP aquifer recession coefficient is set to zero to evaluate the effect of complete loss of the water that infiltrates through the bioretention and porous parking BMPs. This scenario provides an upper bound for the peak and volume reduction that might be achieved through these BMPs in any particular treatment train and infiltration assumptions. Another scenario tests the effect of using a recession coefficient of 0.1/hr, which simulates a delayed release from aquifer storage of water infiltrated through bioretention and porous parking BMPS.

The combinations of the three alternative assumptions result in a total of eight unique model runs for each treatment train – sixteen in total (Table 6). These scenarios were conducted assuming that the catchment was dominated by till soils with relatively low permeability. Scenarios were also run that assumed poorly or very poorly draining D soils. These scenarios assume that BMP infiltration is captured in an underdrain and routed downstream to the outlet so the BMP aquifer recession coefficient is not considered in these scenarios. This resulted in a total of 24 different scenarios evaluated for this pilot study.

Table 6. Summary of scenarios evaluated in this pilot study.

Treatment Train	On-site Detention	Pervious Treatment	Aquifer Recession Coefficient (/hr)
Green	Rain Barrel	0	0
Green	Rain Barrel	0	0.1
Green	Rain Barrel	80	0
Green	Rain Barrel	80	0.1
Green	Cistern	0	0
Green	Cistern	0	0.1
Green	Cistern	80	0
Green	Cistern	80	0.1
Green + Gray	Rain Barrel	0	0
Green + Gray	Rain Barrel	0	0.1
Green + Gray	Rain Barrel	80	0
Green + Gray	Rain Barrel	80	0.1
Green + Gray	Cistern	0	0
Green + Gray	Cistern	0	0.1
Green + Gray	Cistern	80	0
Green + Gray	Cistern	80	0.1

2.8 Analysis/Synthesis of Results

The output from a SUSTAIN cost-effectiveness model run consists of hourly time series files for the pre-developed forested catchment condition and the current or existing catchment condition.[21] In addition, the effectiveness, total cost and cost breakdown by BMP type for

[21] Because the aquifer component is used in these scenarios, the forested model output does not include the subsurface flow time series. Therefore, a separate model run was set up to provide a forested output time series for comparison to current/existing condition and "Best" solution model runs.

all of the scenarios and a subset of optimal (Best) solutions over the range of most cost effective solutions is also provided. An Excel-based post-processor is provided with the SUSTAIN distribution that allows for the analysis of the model output and selection of any particular "Best" solution so the scenario can be run again to obtain an output time series file for further analysis of that particular BMP scenario (Figure 13). For this pilot study, best professional judgment was used to select the "Best" solution that was the most effective at the least cost.

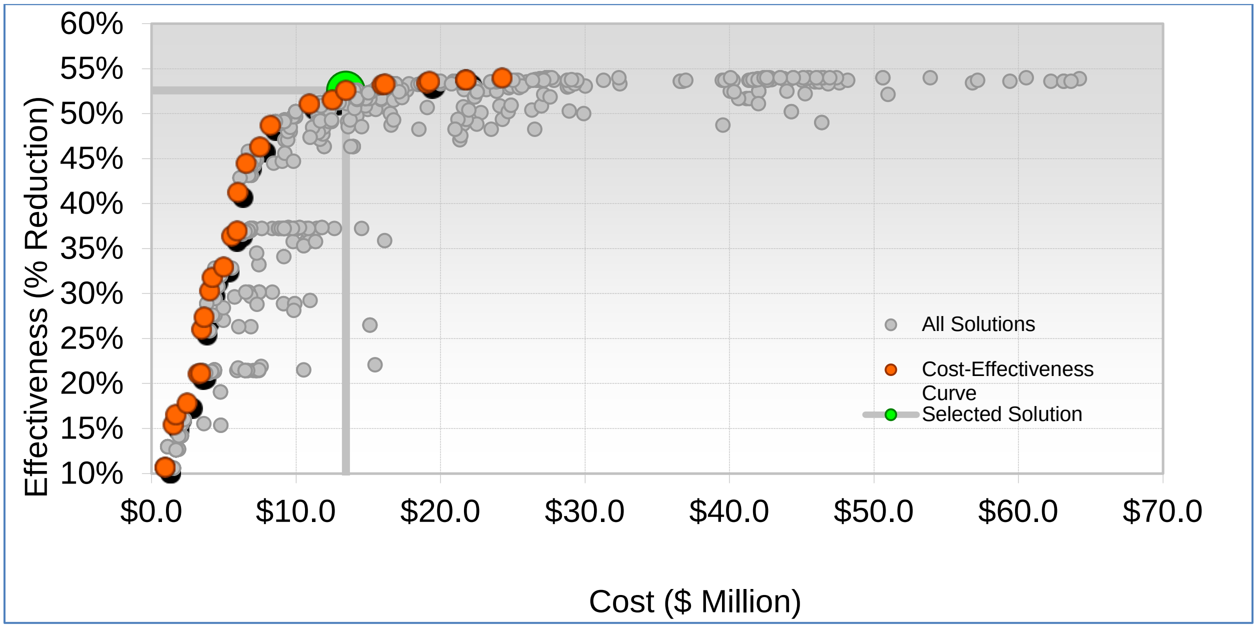

Figure 13. Hypothetical cost-effectiveness curve showing a selected "Best" solution (green symbol at intersection of grey lines drawn from the x and y axes) on the cost-effectiveness curve.

SUSTAIN only outputs the average number of annual HPCs over the simulation period. SUSTAIN does not provide a time series output of the annual HPCs over the simulation period. Post-processing tools were developed by King County to provide for further analysis of the SUSTAIN output, including time series comparisons of HPCs among pre-development, existing conditions and selected optimum scenarios. The post-processing tools also provide the ability to calculate the other two hydrologic metrics selected for evaluation in this study (HPR and PEAK:BASE) and the ability to extrapolate to potential improvements in B-IBI scores (Horner 2013). Graphical comparisons of pre-development, current condition and selected "Best" solution flow duration curves were also generated from the time series output in order to compare SUSTAIN results with King County and Ecology stormwater management design standards.[22]

Analysis of potential water quality benefits (turbidity, copper and zinc) were also extrapolated from modeled TSS concentrations using the regression equations developed by Horner (2013) for this project. These extrapolations generally assume that TSS will continue to be a reasonable surrogate for turbidity, copper and zinc concentrations through the treatment system. In general, the extrapolation to water quality benefits is meant to provide a first-order estimate of the potential reductions in loads and concentrations of sediment and trace metals, with uncertainty in these predictions increasing from TSS and turbidity to trace metals.

[22] King County's Surface Water Design Manual:
http://www.kingcounty.gov/environment/waterandland/stormwater/documents/surface-water-design-manual.aspx

Ecology's Stormwater Management Manual for Western Washington:
http://www.ecy.wa.gov/programs/wq/stormwater/manual.html

3.0. RESULTS AND DISCUSSION

Results are presented and discussed, focusing on the results for the twenty-four SUSTAIN cost-effectiveness optimization scenarios conducted assuming the predominance of low permeability till soils within the pilot study catchment. The following sections cover 1) effectiveness and costs, 2) potential improvement in B-IBI scores, 3) reductions in mean flow rate and volume, 4) potential water quality benefits and 5) comparison of flow duration curves for selected scenarios.

3.1 Effectiveness and Costs

A summary of the results of the cost-effectiveness optimization for the sixteen scenarios (assuming low permeability till soils) for a selected "Best" solution for each scenario are provided in Table 7. Also included in Table 7 are the average HPC, HPR and PEAK:BASE for the "Best" scenario results, with average current condition/forested condition results for these hydrologic metrics provided below the column header for comparison purposes. The cost-effectiveness curves and an illustration of the cost of each treatment type for all of the Best solutions along the cost-effectiveness curve are provided in Appendix C for each of the 16 scenarios evaluated. The selected "Best" solution used to develop the detailed results for each scenario is also show in the figures presented in Appendix C.

The percent effectiveness (i.e., the relative ability of a selected scenario solution to reduce HPC from current conditions) ranged from 31 to 55 percent (i.e., up to a 55 percent reduction of HPC; from 19 to 8). Total 30-yr life-cycle costs generally reflected the maximum effectiveness achieved in any particular scenario and ranged from $4.8 to $14.7 million (M) (roughly $20,000 to $65,000 per acre).

Also included in Table 7 is a breakdown for each selected "Best" solution of the number and total costs for each BMP type. As mentioned above, a particular BMP may not be represented in any particular optimization solution. Porous parking areas were identified in only two of the "Best" solutions selected (see Table 7). This may be due to the relatively small area represented by commercial/industrial land use in this catchment. Likewise, rain barrels were not included in the selected "Best" solutions in three of the four Green only and three of the four Green+Gray scenarios.

The two most effective scenarios with respect to reduction in HPC (55% reduction in HPC at a cost of about $10.7 M) were Green+Gray treatment trains, one with cisterns and the other with rain barrels (although no rain barrels were selected in this solution), treating an additional 80 percent of the pervious surface runoff and assuming that none of the BMP infiltration returns to the catchment outlet (Scenarios 11 and 15 in Table 7). These scenarios were also relatively effective in reducing PEAK:BASE, which serves as an independent check on the potential for improvement in B-IBI scores at the catchment outlet for scenarios in which HPC is substantially reduced (Horner 2013). Interestingly, lower PEAK:BASE was achieved by a less expensive "Best" model run representing Scenario 16 (Green+Gray, Cistern, +80% pervious, RC=0.1/hr; $5.9 M), which also produced relatively low average HPC and HPR.

Other scenarios were almost as effective at reducing HPC, but they were not as effective in reducing PEAK:BASE. For example, the most expensive solution selected (Scenario 7 in Table 7) (Green only, cistern, 80 percent pervious treatment, zero infiltration return at a cost of $14.7 M) was almost as effective as the two most effective scenarios described above, but was not nearly as effective at reducing PEAK:BASE. A few other scenarios, including Green only and scenarios in which only EIA were treated, were almost as effective at reducing HPC and were also less costly. However, these scenarios were not as effective at reducing PEAK:BASE.

Table 8 provides a more detailed breakdown of costs for the selected "Best" scenario solutions. Costs are broken down into public and private costs for facilities on private land (rain barrels, cisterns and rain gardens) that reflect private capital costs and public I&E costs. Total costs are also summarized for private costs and public costs broken down into capital, O&M, I&E and total public costs. The cost breakdown for Scenarios 11 and 15 were very similar, with the private capital costs being slightly higher for Scenario 15 ($3.09 vs $2.13 M) and the total public costs being very similar ($10.85 vs $10.64 M).

Table 9 and Table 10 provide the same effectiveness and cost summaries of the selected "Best" solutions of the eight SUSTAIN optimization runs conducted under the assumption that the catchment is very poorly drained Type D soils. Not surprisingly, the lack of any assumed infiltration from the bioretention BMPs resulted in somewhat less to much lower effectiveness compared to the sixteen Till scenarios. The difference in effectiveness between the Green and Green+Gray scenarios was also more distinct, with the "Best" Green only scenario being only 20 percent effective in reducing HPC (Cistern, treating 80% pervious runoff, see Table 9). The Green+Gray scenarios were similar in cost and effectiveness (43-45%, $5.2-$7.9M), with solutions that favored detention ponds exclusively (Rain Barrel scenarios) or as part of a "Best" solution (Cistern scenarios). As an example, the most effective selected "Best" scenario (45% effective) included a mix of onsite detention, roadside bioretention and detention ponds at a cost of $7.9 M (Table 9). The "Best" Green+Gray Rain Barrel scenario solutions (that exclusively selected detention pond treatment) were slightly more effective than the Till scenarios in reducing PEAK:BASE; from 45 under Current conditions to as low as 28, whereas the lowest PEAK:BASE in the Till scenarios was 32.

The detailed cost breakdown in Table 10 indicates that the majority of the costs for the more effective "Best" solutions are public rather than private and dominated by public capital costs reflecting the selection of detention ponds as a significant method of treatment in these scenarios.

Table 7. Summary of "Best" solutions for cost-effectiveness optimization scenarios for low permeability till soils.

	Scenario	Best sol. No.	Eff/ %Red	Total Cost	Onsite Detention		Rain Garden		Porous Parking		Roadside Bioretention		Detention Pond		HPC	HPR	PEAK : BASE
Green only				**($M)**	**($M)**	**#units**	**($M)**	**#units**	**($M)**	**#units**	**($M)**	**#units**	**($M)**	**#units**	**19/4 a**	**257/80 a**	**45/6 a**
1	Rain Barrel, EIA only, RC = 0.0/hr	27	43%	$ 6.9	$ -	(0)	$ 3.487	(500)	$ -	(0)	$ 3.404	(540)	na	-	13	183	40
2	Rain Barrel, EIA only, RC = 0.1/hr	4	31%	$ 6.1	$ -	(0)	$ 3.487	(500)	$ -	(0)	$ 2.648	(420)	na	-	12	200	42
3	Rain Barrel, +80% pervious, RC = 0.0/hr	5	53%	$13.4	$ -	(0)	$10.041	(1440)	$ -	(0)	$ 3.404	(540)	na	-	14	196	38
4	Rain Barrel, +80% pervious, RC = 0.1/hr	11	32%	$ 7.1	$ 0.368	(240)	$ 5.021	(720)	$ -	(0)	$ 1.702	(270)	na	-	17	236	41
5	Cistern, EIA only, RC = 0.0/hr	7	45%	$ 7.3	$ 0.961	(330)	$ 3.312	(475)	$ -	(0)	$ 3.026	(480)	na	-	10	159	48
6	Cistern, EIA only, RC = 0.1/hr	10	35%	$ 6.6	$ 1.049	(360)	$ 3.312	(475)	$ -	(0)	$ 2.269	(360)	na	-	14	199	39
7	Cistern, +80% pervious, RC = 0.0/hr	21	53%	$14.7	$ 0.874	(300)	$10.041	(1440)	$ -	(0)	$ 3.782	(600)	na	-	8	127	42
8	Cistern, +80% pervious, RC = 0.1/hr	1	36%	$ 8.5	$ 1.223	(420)	$ 5.021	(720)	$ 0.774	(90)	$ 1.513	(240)	na	-	11	174	42
Green + Gray																	
9	Rain Barrel, EIA only, RC = 0.0/hr	9	53%	$ 9.7	$ -	(0)	$ 3.312	(475)	$ -	(0)	$ 1.702	(270)	$ 4.195	(40)	12	182	39
10	Rain Barrel, EIA only, RC = 0.1/hr	23	43%	$ 4.8	$ 0.184	(120)	$ -	(0)	$ -	(0)	$ 0.378	(60)	$ 4.195	(40)	10	160	33
11	Rain Barrel, +80% pervious, RC = 0.0/hr	24	55%	$10.6	$ -	(0)	$ 5.021	(720)	$ 0.774	(90)	$ 1.702	(270)	$ 3.146	(30)	10	157	34
12	Rain Barrel, +80% pervious, RC = 0.1/hr	28	32%	$ 6.3	$ -	(0)	$ 5.021	(720)	$ -	(0)	$ 1.324	(210)	$ -	(0)	17	241	41
13	Cistern, EIA only, RC = 0.0/hr	20	53%	$ 8.9	$ 0.524	(180)	$ 3.487	(500)	$ -	(0)	$ 1.702	(270)	$ 3.146	(30)	8	136	36
14	Cistern, EIA only, RC = 0.1/hr	3	45%	$ 5.5	$ 0.961	(330)	$ -	(0)	$ -	(0)	$ 0.378	(60)	$ 4.195	(40)	10	151	32
15	Cistern, +80% pervious, RC = 0.0/hr	23	55%	$10.8	$ 0.787	(270)	$ 5.021	(720)	$ -	(0)	$ 1.891	(300)	$ 3.146	(30)	8	129	35
16	Cistern, +80% pervious, RC = 0.1/hr	2	45%	$ 5.9	$ 1.486	(510)	$ -	(0)	$ -	(0)	$ 0.189	(30)	$ 4.195	(40)	10	145	33

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent.

M = Millions; EIA = Effective Impervious Area; RC = Aquifer Recession Coefficient; HPC = High Pulse Count; HPR = High Pulse Range; PEAK:BASE = ratio of 2-yr peak return flow to winter base flow

a Current condition/ fully-forested condition hydrologic metric values for comparison

Table 8. Detailed cost breakdown for "Best" cost-effectiveness optimization scenarios for till soils. All costs in millions of dollars.

	Scenario	Best sol. No.	Eff/ %Red	Total Cost ($M)	Onsite Detention		Rain Garden		Porous Parking		Road. Bioret.	Detention Pond		Total				
														Priv.	Public			
Green only					Priv.	Pub.	Priv.	Pub.	Priv.	Pub.	Pub.	Pub.	Land	Cap.	Cap.	O&M	I&E	Total
1	Rain Barrel, EIA only, RC = 0.0/hr	27	43%	$ 6.9	$ -	$ -	$ 1.85	$ 1.64	$ -	$ -	$ 3.40	na	na	$ 1.85	$ 1.08	$ 0.91	$ 3.05	$ 5.05
2	Rain Barrel, EIA only, RC = 0.1/hr	4	31%	$ 6.1	$ -	$ -	$ 1.85	$ 1.64	$ -	$ -	$ 2.65	na	na	$ 1.85	$ 0.84	$ 0.71	$ 2.74	$ 4.29
3	Rain Barrel, +80% pervious, RC = 0.0/hr	5	53%	$13.4	$ -	$ -	$ 5.32	$ 4.73	$ -	$ -	$ 3.40	na	na	$ 5.32	$ 1.08	$ 0.91	$ 6.14	$ 8.13
4	Rain Barrel, +80% pervious, RC = 0.1/hr	11	32%	$ 7.1	$ 0.05	$ 0.32	$ 2.36	$ 2.36	$ -	$ -	$ 1.70	na	na	$ 2.71	$ 0.54	$ 0.46	$ 3.38	$ 4.38
5	Cistern, EIA only, RC = 0.0/hr	7	45%	$ 7.3	$ 0.53	$ 0.43	$ 1.75	$ 1.56	$ -	$ -	$ 3.03	na	na	$ 2.28	$ 0.96	$ 0.81	$ 3.25	$ 5.02
6	Cistern, EIA only, RC = 0.1/hr	10	35%	$ 6.6	$ 0.58	$ 0.47	$ 1.75	$ 1.56	$ -	$ -	$ 2.27	na	na	$ 2.33	$ 0.72	$ 0.61	$ 2.97	$ 4.30
7	Cistern, +80% pervious, RC = 0.0/hr	21	53%	$14.7	$ 0.48	$ 0.39	$ 5.32	$ 4.73	$ -	$ -	$ 3.78	na	na	$ 5.80	$ 1.20	$ 1.02	$ 6.69	$ 8.90
8	Cistern, +80% pervious, RC = 0.1/hr	1	36%	$ 8.5	$ 0.67	$ 0.55	$ 2.66	$ 2.36	$ 0.18	$ 0.59	$ 1.51	na	na	$ 3.51	$ 0.48	$ 0.41	$ 4.13	$ 5.02
Green + Gray																		
9	Rain Barrel, EIA only, RC = 0.0/hr	9	53%	$ 9.7	$ -	$ -	$ 0.37	$ 0.33	$ -	$ -	$ 0.38	$ 1.23	$ 0.87	$ 0.37	$ 2.18	$ 0.14	$ 0.49	$ 2.81
10	Rain Barrel, EIA only, RC = 0.1/hr	23	43%	$ 4.8	$ 0.29	$ 0.24	$ -	$ -	$ -	$ -	$ 0.38	$ 2.46	$ 1.74	$ 0.03	$ 4.24	$ 0.18	$ 0.31	$ 4.73
11	Rain Barrel, +80% pervious, RC = 0.0/hr	24	55%	$10.6	$ -	$ -	$ 2.66	$ 2.36	$ 0.18	$ 0.59	$ 1.70	$ 1.84	$ 1.30	$ 2.84	$ 3.63	$ 0.52	$ 3.66	$ 7.80
12	Rain Barrel, +80% pervious, RC = 0.1/hr	28	32%	$ 6.3	$ -	$ -	$ 2.66	$ 2.36	$ -	$ -	$ 1.32	$ -	$ -	$ 2.66	$ 0.42	$ 0.18	$ 2.91	$ 3.69
13	Cistern, EIA only, RC = 0.0/hr	20	53%	$ 8.9	$ 0.29	$ 0.24	$ 1.85	$ 1.64	$ -	$ -	$ 1.70	$ 1.84	$ 1.30	$ 2.13	$ 3.63	$ 0.57	$ 2.58	$ 6.73
14	Cistern, EIA only, RC = 0.1/hr	3	45%	$ 5.5	$ 0.53	$ 0.43	$ -	$ -	$ -	$ -	$ 0.38	$ 2.46	$ 1.74	$ 0.53	$ 4.24	$ 0.18	$ 0.59	$ 5.01
15	Cistern, +80% pervious, RC = 0.0/hr	23	55%	$10.8	$ 0.43	$ 0.35	$ 2.66	$ 2.36	$ -	$ -	$ 1.89	$ 1.84	$ 1.30	$ 3.09	$ 3.69	$ 0.57	$ 3.50	$ 7.76
16	Cistern, +80% pervious, RC = 0.1/hr	2	45%	$ 5.9	$ 0.82	$ 0.67	$ -	$ -	$ -	$ -	$ 0.19	$ 2.46	$ 1.74	$ 0.82	$ 4.18	$ 0.13	$ 0.75	$ 5.05

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent.

M = Millions; EIA = Effective Impervious Area; RC = Aquifer Recession Coefficient; Priv. = Private costs (Capital costs); Pub. = Public costs (Inspection and Enforcement costs unless otherwise specified); O&M = operations & maintenance costs; I&E = inspections and enforcement cost

Table 9. Summary of "Best" solutions for cost-effectiveness optimization scenarios for very poorly drained Type D soils.

	Scenario	Best sol. No.	Eff/ %Red	Total Cost	Onsite Detention		Rain Garden		Porous Parking		Roadside Bioretention		Detention Pond		HPC	HPR	PEAK : BASE
Green only				($M)	($M)	#units	($M)	#units	($M)	#units	($M)	#units	($M)	#units	19/4 a	257/80 a	45/6 a
1	Rain Barrel, EIA only	1	3%	$10.0	$ 3.311	(2160)	$ 3.138	(450)	$ -	(0)	$ 3.593	(570)	na	-	17	244	45
2	Rain Barrel, +80% pervious	2	14%	$53.7	$ 3.127	(2040)	$50.206	(7200)	$ -	(0)	$ 0.378	(60)	na	-	15	183	45
3	Cistern, EIA only	25	7%	$ 1.0	$ 0.699	(240)	$ 0.349	(50)	$ -	(0)	$ -	(0)	na	-	17	227	44
4	Cistern, +80% pervious	7	20%	$48.4	$ 0.699	(240)	$47.695	(6840)	$ -	(0)	$ -	(0)	na	-	14	168	45
Green + Gray																	
5	Rain Barrel, EIA only	20	43%	$ 5.2	$ -	(0)	$ -	(0)	$ -	(0)	$ -	(0)	$ 5.243	(50)	10	155	28
6	Rain Barrel, +80% pervious	12	43%	$ 5.2	$ -	(0)	$ -	(0)	$ -	(0)	$ -	(0)	$ 5.243	(50)	10	155	29
7	Cistern, EIA only	20	45%	$ 7.9	$ 1.660	(570)	$ -	(0)	$ -	(0)	$ 1.349	(330)	$ 4.195	(40)	10	144	31
8	Cistern, +80% pervious	27	44%	$ 5.2	$ 1.049	(360)	$ -	(0)	$ -	(0)	$ -	(0)	$ 4.195	(40)	10	150	34

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent.

M = Millions; EIA = Effective Impervious Area; RC = Aquifer Recession Coefficient; HPC = High Pulse Count; HPR = High Pulse Range; PEAK:BASE = ratio of 2-yr peak return flow to winter base flow

a Current condition/ fully-forested condition hydrologic metric values for comparison

Table 10. Detailed cost breakdown for "Best" cost-effectiveness optimization scenarios for very poorly drained Type D soils. All costs in millions of dollars.

	Scenario	Best sol. No.	Eff/ %Red	Total Cost ($M)	Onsite Detention		Rain Garden		Porous Parking		Road. Bioret.	Detention Pond		Total				
														Priv.	Public			
Green only					Priv.	Pub.	Priv.	Pub.	Priv.	Pub.	Pub.	Pub.	Land	Cap.	Cap.	O&M	I&E	Total
1	Rain Barrel, EIA only	1	3%	$10.0	$ 0.48	$ 2.84	$ 1.66	$ 1.64	$ -	$ -	$ 3.59	na	na	$ 2.14	$ 1.14	$ 0.96	$ 5.80	$ 7.91
2	Rain Barrel, +80% pervious	2	14%	$53.7	$ 0.45	$ 2.68	$26.58	$ 2.36	$ -	$ -	$ 0.38	na	na	$27.02	$ 0.12	$ 0.10	$26.47	$26.69
3	Cistern, EIA only	25	7%	$ 1.0	$ 0.38	$ 0.32	$ 0.19	$ 1.56	$ -	$ -	$ -	na	na	$ 0.57	$ -	$ -	$ 0.48	$ 0.48
4	Cistern, +80% pervious	7	20%	$48.4	$ 0.38	$ 0.32	$25.25	$ 2.36	$ -	$ -	$ -	na	na	$25.63	$ -	$ -	$22.76	$22.76
Green + Gray																		
5	Rain Barrel, EIA only	20	43%	$ 5.2	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 3.07	$ 2.17	$ -	$ 5.15	$ 0.10	$ -	$ 5.25
6	Rain Barrel, +80% pervious	12	43%	$ 5.2	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 3.07	$ 2.17	$ -	$ 5.15	$ 0.10	$ -	$ 5.25
7	Cistern, EIA only	20	45%	$ 7.9	$ 0.91	$ 0.75	$ -	$ -	$ -	$ -	$ 2.08	$ 2.46	$ 1.74	$ 0.91	$ 4.78	$ 0.64	$ 1.61	$ 7.94
8	Cistern, +80% pervious	27	44%	$ 5.2	$ 0.58	$ 0.47	$ -	$ -	$ -	$ -	$ -	$ 2.46	$ 1.74	$ 0.58	$ 4.12	$ 0.08	$ 0.47	$ 5.25

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent.

M = Millions; EIA = Effective Impervious Area; RC = Aquifer Recession Coefficient; Priv. = Private costs (Capital costs); Pub. = Public costs (Inspection and Enforcement costs unless otherwise specified); O&M = operations & maintenance costs; I&E = inspections and enforcement cost

3.2 Potential Improvement in B-IBI Scores

Table 11 provides a summary of predictions in potential improvement in B-IBI scores based on the average HPC, HPR and PEAK:BASE results for the "Best" cost-effectiveness optimization scenarios assuming Till soils. Note that these predictions are qualified as being based on providing hydrologic conditions that are necessary, but not necessarily sufficient, for improvements in B-IBI scores (Horner 2013). There may be other limiting factors in any particular catchment that might prevent substantial improvements in B-IBI scores, such as degraded riparian areas, poor water quality or altered stream channel geomorphology. Regardless, the underlying premise is that hydrologic restoration to conditions closer to that which occurred prior to significant human disturbance and development is required before any substantial biological improvement can be achieved.

Results for predictions based on HPC (and HPR) are presented as upper and lower confidence predictions (as percent of maximum possible B-IBI score) that reflect the uncertainty inherent in the scatter of the underlying data used to develop the regression relationships between HPC (and HPR) and B-IBI scores. Predictions are presented as percent of maximum B-IBI score because of the difference in the underlying B-IBI data available for developing relationships with HPC/HPR and PEAK:BASE; the PEAK:BASE relationship was developed earlier when the maximum B-IBI score was 45 rather than 50 (Horner 2013). The predictions for B-IBI score improvement using PEAK:BASE are based on a logistic regression equation that predicts the probability (in percent) of improving B-IBI scores to greater than or equal to 40 percent of the maximum possible score (Horner 2013).

Horner (2013) developed logistic regressions for HPC and HPR that could also be employed to provide probabilistic estimates of improvement in B-IBI scores, but the application of these statistical models are not explored in this report. Rather, example results are provided here to illustrate the concepts and type of post-processing analyses that can be conducted with respect to predicting B-IBI score improvements.

Predicted improvement in B-IBI scores based on "Best" scenario HPC results ranged from as high as 76 percent of maximum (90% upper confidence limit) to as low as 17 percent of maximum (90% lower confidence limit). Narrower ranges in upper and lower bound predictions within the maximum limits of the 90% confidence interval were predicted at the 80 and 60% confidence level. The range in maximum upper and lower confidence prediction range based on HPR was slightly larger – 85 to 16 percent. The predictions for HPR are fairly similar to those for HPC, which is not unexpected as these two metrics have been found to be fairly redundant (DeGasperi et al. 2009).

Predicted probability in the improvement of B-IBI scores based on PEAK:BASE (scores greater or equal to 40% of maximum) ranged from 27 to 53 percent, with predictions that were not always consistent with those based on HPC and HPR. These differences provide support to the concept that PEAK:BASE is an independent indictor of the potential for improvement in B-IBI scores (Horner 2013).

Predictions based on HPC for Scenario 15 (one of the two highest performing scenarios highlighted above) indicate an upper and lower confidence improvement in maximum B-

IBI score of between 76 and 37 percent (90% confidence), which on a B-IBI scale of 50 would be classified as anywhere from Poor (B-IBI between 18 and 26) to Good (B-IBI between 38 and 44). The narrower 60% confidence interval predicts scores between Poor and Fair (B-IBI between 28 and 36). The prediction based on PEAK:BASE is that there is an 47% probability that B-IBI scores will improve from essentially Very Poor to Poor or above.

3.3 Changes in Mean Flow/Volume Reduction

Table 12 provides a summary of the differences in mean flow among the Till scenarios and for modeled Current and Fully-forested conditions. Differences in mean flow among scenarios are consistent with the assumptions regarding aquifer release and the amount of runoff routed to treatment (i.e., assuming BMP infiltration does not reach the outlet, RC = 0.0/hr, and routing additional pervious runoff to treatment resulted in lower predicted mean flow). These differences in mean flow reflect the reduction in the total volume of water delivered to the downstream assessment point in any particular scenario. For example, mean flow in all scenarios that incorporated an aquifer recession constant of 0.1/hr had the same mean flow as the current condition model run (0.98 cfs). The largest reductions in mean flow occurred in the scenarios that included routing 80% of the pervious runoff to treatment and that assumed no BMP infiltration was routed to the downstream assessment point. This was particularly evident in the scenarios that included cisterns for onsite detention; Scenarios 7 and 15 were particularly effective in reducing mean flow and flow volume – to 0.72 and 0.77 cfs, respectively.

These differences in flow are generally reflected in the predicted potential for improvements in water quality, since filtration and volume reduction through infiltration translates into reductions in concentration and mass of TSS and by the extrapolation equations to reductions in turbidity and concentrations and mass of copper and zinc. These potential improvements are presented and discussed in the following section.

3.4 Potential Improvement in Water Quality

Table 12 also provides a summary of predictions in potential improvement in water quality based on the modeled hourly TSS concentration results for the “Best” cost-effectiveness optimization scenarios. Extrapolation from TSS concentration to turbidity, total copper and zinc and dissolved copper and zinc are based on relationships developed by Horner (2013). Results are presented for potential reduction in TSS, total copper, and total zinc loads (in kg per day) and for reduction in the frequency of exceedances of water quality standards for turbidity, dissolved copper and dissolved zinc. Loads and frequency of exceedance for current condition SUSTAIN model output are also provided for comparison to scenario results. Differences in modeled mean flow for current and fully-forested cases as well as for the sixteen scenarios are also provided in Table 12.

Consistent with results for reductions in flow volume, Scenarios 7 and 15 were the best of the sixteen Till scenarios with respect to improving water quality (Table 12). TSS loads were predicted to be reduced by approximately 80 percent and total copper and zinc loads were predicted to be reduced by 30 to 40 percent.

Table 11. Summary of potential improvement in B-IBI scores based on relationships developed by Horner (2013) for "Best" cost-effectiveness optimization scenarios for till soils.

	Scenarios	Best Sol. No.	Eff/ %Red	Total Cost ($M)	% of Maximum B-IBI (High Pulse Count) UCL 90%	LCL 90%	UCL 80%	LCL 80%	UCL 60%	LCL 60%	% of Maximum B-IBI (High Pulse Range) UCL 90%	LCL 90%	UCL 80%	LCL 80%	UCL 60%	LCL 60%	PEAK : BASE a
	Current Condition		-	-	47%	16%	41%	18%	36%	21%	51%	14%	48%	19%	44%	21%	-
	Fully-forested condition		-	-	100%	52%	86%	56%	79%	60%	100%	48%	97%	56%	90%	60%	99%
Green only																	
1	Rain Barrel, EIA only, RC = 0.0/hr	27	43%	$ 6.9	60%	24%	54%	27%	47%	30%	68%	24%	64%	30%	60%	32%	38%
2	Rain Barrel, EIA only, RC = 0.1/hr	4	31%	$ 6.1	62%	27%	57%	29%	50%	33%	63%	21%	60%	27%	56%	29%	35%
3	Rain Barrel, +80% pervious, RC = 0.0/hr	5	53%	$13.4	57%	23%	51%	25%	45%	28%	64%	21%	61%	28%	57%	30%	41%
4	Rain Barrel, +80% pervious, RC = 0.1/hr	11	32%	$ 7.1	49%	17%	44%	20%	38%	23%	55%	16%	52%	22%	48%	23%	37%
5	Cistern, EIA only, RC = 0.0/hr	7	45%	$ 7.3	69%	32%	63%	34%	56%	38%	75%	28%	70%	35%	66%	37%	27%
6	Cistern, EIA only, RC = 0.1/hr	10	35%	$ 6.6	57%	23%	51%	25%	45%	28%	64%	21%	60%	27%	56%	29%	40%
7	Cistern, +80% pervious, RC = 0.0/hr	21	53%	$14.7	76%	37%	70%	40%	63%	44%	85%	35%	80%	42%	75%	45%	35%
8	Cistern, +80% pervious, RC = 0.1/hr	1	36%	$ 8.5	65%	29%	60%	32%	53%	35%	70%	25%	66%	32%	62%	34%	35%
Green + Gray																	
9	Rain Barrel, EIA only, RC = 0.0/hr	9	53%	$ 9.7	62%	27%	57%	29%	50%	33%	68%	24%	64%	30%	60%	32%	40%
10	Rain Barrel, EIA only, RC = 0.1/hr	23	43%	$ 4.8	69%	32%	63%	34%	56%	38%	74%	28%	70%	34%	65%	37%	51%
11	Rain Barrel, +80% pervious, RC = 0.0/hr	24	55%	$10.6	69%	32%	63%	34%	56%	38%	75%	28%	71%	35%	66%	38%	49%
12	Rain Barrel, +80% pervious, RC = 0.1/hr	28	32%	$ 6.3	49%	17%	44%	20%	38%	23%	54%	16%	51%	21%	47%	23%	37%
13	Cistern, EIA only, RC = 0.0/hr	20	53%	$ 8.9	76%	37%	70%	40%	63%	44%	82%	33%	77%	40%	72%	43%	45%
14	Cistern, EIA only, RC = 0.1/hr	3	45%	$ 5.5	69%	32%	63%	34%	56%	38%	77%	29%	73%	36%	68%	39%	53%
15	Cistern, +80% pervious, RC = 0.0/hr	23	55%	$10.8	76%	37%	70%	40%	63%	44%	84%	34%	79%	42%	74%	45%	47%
16	Cistern, +80% pervious, RC = 0.1/hr	2	45%	$ 5.9	69%	32%	63%	34%	56%	38%	79%	31%	74%	38%	69%	40%	51%

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent.

M = Millions; UCL = Upper Confidence Limit; LCL = Lower Confidence Limit

a Probability of improving B-IBI scores above 40% of maximum (Horner 2013).

Table 12. Summary of potential improvements in water quality [total suspended solids (TSS), turbidity, copper (Cu) and zinc (Zn)] based on relationships developed by Horner (2013) for "Best" cost-effectiveness optimization scenarios on till soils.

										Diss. Copper (Cu)		Diss. Zinc (Zn)	
		Best			Mean Flow	TSS Load	TCu Load	TZn Load	Turbidity Std	Acute Std a	Chronic Std a	Acute Std a	Chronic Std a
Scenarios		Sol. No.	Eff/ %Red	Total Cost ($M)	cfs		kg/d			Percent of time exceeded			
	Current Condition		-	-	0.98	33.2	0.009	0.043	7%	0.0%	0.0%	0.1%	0.0%
	Fully-forested condition		-	-	0.83	-	-	-	-	-	-	-	-
Green only													
1	Rain Barrel, EIA only, RC = 0.0/hr	27	43%	$ 6.9	0.87	18.4	0.007	0.033	5%	0.0%	0.0%	0.0%	0.0%
2	Rain Barrel, EIA only, RC = 0.1/hr	4	31%	$ 6.1	0.98	13.4	0.008	0.033	2%	0.0%	0.0%	0.1%	0.0%
3	Rain Barrel, +80% pervious, RC = 0.0/hr	5	53%	$13.4	0.89	19.5	0.007	0.034	5%	0.0%	0.0%	0.0%	0.0%
4	Rain Barrel, +80% pervious, RC = 0.1/hr	11	32%	$ 7.1	0.98	26.3	0.008	0.040	6%	0.0%	0.0%	0.1%	0.0%
5	Cistern, EIA only, RC = 0.0/hr	7	45%	$ 7.3	0.80	11.8	0.006	0.027	2%	0.0%	0.0%	0.1%	0.0%
6	Cistern, EIA only, RC = 0.1/hr	10	35%	$ 6.6	0.98	22.1	0.008	0.037	6%	0.0%	0.0%	0.1%	0.0%
7	Cistern, +80% pervious, RC = 0.0/hr	21	53%	$14.7	0.72	5.3	0.005	0.022	0%	0.0%	0.0%	0.0%	0.0%
8	Cistern, +80% pervious, RC = 0.1/hr	1	36%	$ 8.5	0.97	13.0	0.008	0.033	2%	0.0%	0.0%	0.1%	0.0%
Green + Gray													
9	Rain Barrel, EIA only, RC = 0.0/hr	9	53%	$ 9.7	0.96	16.1	0.008	0.034	4%	0.0%	0.0%	0.0%	0.0%
10	Rain Barrel, EIA only, RC = 0.1/hr	23	43%	$ 4.8	0.97	12.6	0.008	0.032	3%	0.0%	0.0%	0.0%	0.0%
11	Rain Barrel, +80% pervious, RC = 0.0/hr	24	55%	$10.6	0.93	10.8	0.007	0.030	3%	0.0%	0.0%	0.0%	0.0%
12	Rain Barrel, +80% pervious, RC = 0.1/hr	28	32%	$ 6.3	0.98	27.5	0.008	0.040	6%	0.0%	0.0%	0.1%	0.0%
13	Cistern, EIA only, RC = 0.0/hr	20	53%	$ 8.9	0.80	7.3	0.006	0.025	1%	0.0%	0.0%	0.0%	0.0%
14	Cistern, EIA only, RC = 0.1/hr	3	45%	$ 5.5	0.97	11.8	0.008	0.032	3%	0.0%	0.0%	0.0%	0.0%
15	Cistern, +80% pervious, RC = 0.0/hr	23	55%	$10.8	0.77	5.5	0.006	0.023	1%	0.0%	0.0%	0.0%	0.0%
16	Cistern, +80% pervious, RC = 0.1/hr	2	45%	$ 5.9	0.97	11.6	0.008	0.032	3%	0.0%	0.0%	0.0%	0.0%

Note: Costs presented in millions of dollars are total present value costs over a 30 year lifecycle with a discount rate of 5 percent (M = Millions of dollars)

[a] Percent of time acute and chronic standards for dissolved copper and zinc based on equations provided in 173-201A WAC Table 204(3) assuming a hardness of 25 mg/L for the acute standard and 50 mg/L for the chronic standard. Turbidity standard based on core summer salmonid habitat (Table 200 (1)(e)), which specifies that turbidity shall not exceed 5 NTU over background when background is 50 NTU or less and not to exceed a 10 percent increase when background is above 50 NTU.

3.5 Flow Duration Comparisons of Selected Scenarios

Although all three hydrologic metrics evaluated above are correlated with B-IBI scores, historically, the emphasis on stormwater management has been from a geomorphic perspective that emphasizes the reduction in flows over a broad range to reduce physical stream disturbance (Booth 1990; Roesner et al. 2001). For example, King County's stormwater design standards[23] include requirements for matching flow duration curves within a specified range of flows. The detention ponds designed for use in SUSTAIN (describe in Section 2.2.4 above) were sized to match the Fully-forested flow duration curve from 50 percent of the 2-yr return flow to the 50-yr return flow. Ecology has proposed an additional standard for Western Washington in the interest of protecting stream biological resources– matching the fully-forested flow duration curve between 8 percent of the 2-yr return flow to half of the 2-yr return flow.

Figure 14 illustrates how one of the "Best" solution scenarios performs with respect to these flow duration targets. Interestingly, even the Current (Existing) condition flow duration meets the lower end of the proposed Ecology standard, due to the significant reduction in low flow that occurs under these highly developed vs. fully-forested conditions. This may not always be the case in reality due to the confounding influence of potable and wastewater management activities in any particular basin (King County 2010, Hamel et al. 2013).[24] Regardless, the "Best" solution for Scenario 15 resulted in further reductions in flow duration between 50 and 8 percent of the 2-yr return flow so that the flow duration curve would almost meet this portion of the standard. It does not appear that the standard between 50 percent of the 2-yr and the 50-yr return flow would be met, although the duration of high flows is reduced below those of Current flow conditions.

Figure 15 illustrates the flow duration curves for the selected "Best" solution from Scenario 16, which differed from Scenario 15 only by the aquifer recession coefficient (0.1/hr vs. 0.0/hr). This scenario solution was much cheaper than Scenario 15 ($5.9 vs 10.8 M), but also less effective with respect to HPC, HPR and PEAK:BASE (Table 7). The flow duration curve for the selected "Best" solution in Scenario 16 did not meet the flow duration standards, except at the lowest flows. This was due to the storage and then delayed release of water from the aquifer. The delayed release did improve lower flows relative to the Current modeled condition. These comparisons emphasize the importance of understanding the ultimate fate of infiltrated water as this can have a significant effect on

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[23] King County Surface Water Design Manual (2009) http://www.kingcounty.gov/environment/waterandland/stormwater/documents/surface-water-design-manual.aspx

[24] Reductions in base flow, particularly losses during summer base flow due to reduced infiltration resulting from impervious cover development can be offset by importation of potable water from outside the basin depending on whether the method of treatment is via onsite septic systems or export of wastewater to a treatment system outside of the basin.

the response of the receiving water to any particular treatment approach (Hamel et al. 2013).

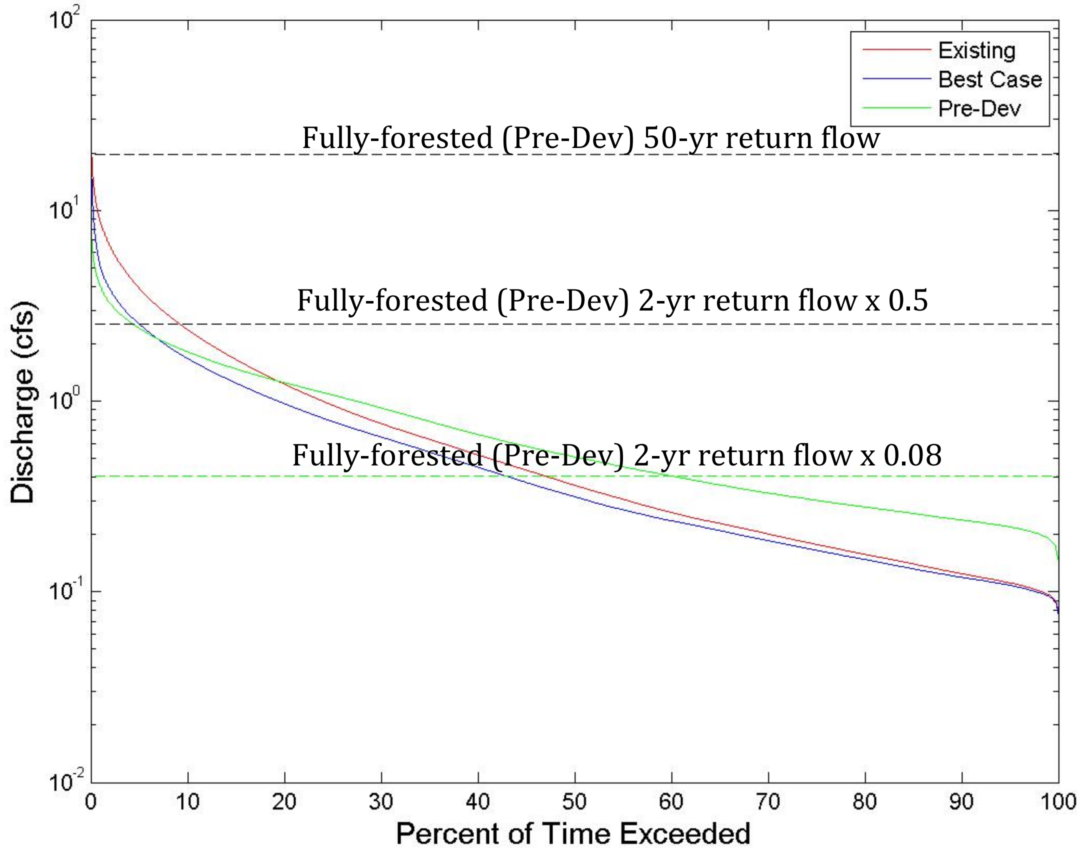

Figure 14. Comparison of flow duration curves for Existing (Current), Best Case and Pre-Dev (Fully-Forested) for Till Green+Gray Scenario 15 (Cistern, +80% pervious, RC = 0.0/hr).

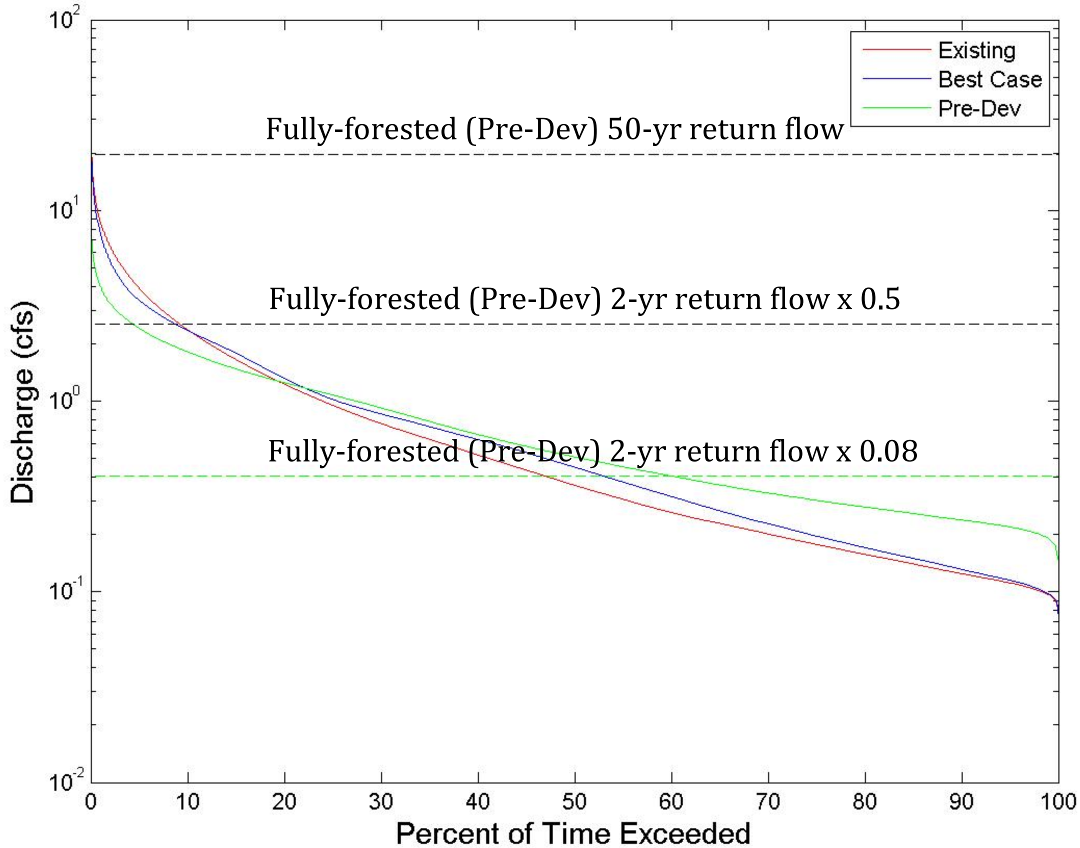

Figure 15. Comparison of flow duration curves for Existing (Current), Best Case and Pre-Dev (Fully-Forested) for Till Green+Gray Scenario 16 (Cistern, +80% pervious, RC = 0.1/hr).

4.0. CONCLUSIONS AND RECOMMENDATIONS

Based on the results presented above, some conclusions and recommendations are provided.

4.1 Conclusions

This pilot study provides a demonstration of a typical SUSTAIN model application and the types of information that can be generated from SUSTAIN cost-effectiveness model runs. The detailed evaluation of sixteen "Best" solutions taken from the sixteen cost-effectiveness scenarios suggest some complex tradeoffs between hydrologic and water quality goals. In general, infiltration BMPs have the potential to substantially improve water quality as long as they are maintained and inspected; the costs of which are accounted for here. However, in soils with low infiltration rates, there appears to be a limit to the hydrologic improvement that can be achieved. It is possible that the relatively developed nature of the catchment also sets some limits on the amount of hydrologic (and potential biological) improvement that can be achieved. Additional SUSTAIN modeling using this pilot study catchment could evaluate the potential improvement that could be achieved if higher BMP infiltration rates were possible (assume BMPs on outwash).

It is also worth reemphasizing that there is a fair amount of uncertainty in the predicted increases in B-IBI scores in response to implementation of any particular scenario; uncertainty not only in the assumption that there is a direct causal relationship between HPC (and HPR/PEAK:BASE) and B-IBI scores, but also in the predictive uncertainty in the log-linear regression equations that attempt to quantify the expected relationship between HPC (or HPR) and B-IBI scores. Even if there is a direct causal relationship between HPC and HPR and declines in B-IBI scores with increased development and associated flashy hydrologic response, there is uncertainty regarding the potential to restore biological integrity to these streams as there are as yet no well documented cases where stormwater BMPs such as those proposed here have resulted in improvements in B-IBI scores. Ultimately, hydrologic restoration to conditions that more closely resemble those of pre-disturbance/development are considered necessary, but not necessarily sufficient for the restoration of stream biological integrity (Horner 2013).

However, these caveats are not meant to discourage such attempts at restoration, but rather to encourage such attempts along with adaptive management approaches that rely on ongoing monitoring and scientific and engineering reassessment at regular intervals (i.e., adaptive management) to assess progress and recommend further improvements as new data and information become available.

4.2 Recommendations

The main limitation to SUSTAIN that has been encountered thus far is the limit of a single orifice in the detention pond BMP. Typically, detention ponds are designed with two or more orifices to control not only the highest flows, but also to control peak flows that occur between the 2-yr (or less) and 50-yr return interval peaks (Roesner et al. 2001). Although SUSTAIN has been modified to allow optimization to HPC, it might be more relevant to optimize the matching of target flow duration curves. Additional improvements to SUSTAIN are under consideration and one or both of these limitations might be addressed as part of SUTAIN support provided by U.S. EPA. As an alternative approach, it would be possible to use Green only assessment point flows from a selected "Best" scenario to design and size a detention facility that would control flows to match a target flow duration curve. It might also be reasonable to re-design the current detention ponds using the Green only assessment point flow rather than runoff from an acre of impervious area as done for this pilot study report. However, it would likely be infeasible to do this for every catchment, especially if multiple scenarios will be considered.

Based on initial evaluation and discussion of the results presented in this pilot study report by the Project Management Team and by participants at the upcoming workshop, the Project Management Team will move forward with modeling additional catchments, focusing on specific catchments throughout the basin that represent distinctly different types of land use/land cover. Discussions at the upcoming workshop will guide additional modeling or analysis that may be incorporated into the final version of this document. The next step of expanding the modeling effort beyond the pilot study catchment will become a larger effort to meet the overall objectives of this study – to develop planning level retrofit cost estimates for WRIA 9 and ultimately for Puget Sound.

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APPENDIX A

Porous Pavement Design Details

Porous Pavement SUSTAIN Modeling

<u>Basic Porous Pavement Model</u>

Basis: King County Surface Water Design Manual and Novelty Hill Road sidewalk and shoulder specifications

Components: Porous concrete or asphalt
Free-draining sand or gravel base
Infiltration-rate-limiting geotextile on outwash soil
(without underdrain)

Applications: Sidewalks, patios, parking lots, and driveways where either the porous pavement provides all required runoff quantity and quality control or a detention pond will be provided to supply any unmet quantity control requirement

Dimensions: Porous concrete—5 inches
Porous asphalt—4 inches
Base—10 inches

<u>Alternative Porous Pavement Model</u>

Basis: Stormwater management manuals' general consensus

Components: Porous concrete or asphalt
Choker course (3/4-inch aggregate)
Reservoir course (1-2-inch aggregate)
Sand treatment layer on outwash soil
Infiltration-rate-limiting geotextile on outwash soil
(without underdrain)

Applications: Same as basic model when the basic model cannot meet the quantity control requirement and using the alternative model is more economical than providing a detention pond to do so

Dimensions: Porous concrete—5 inches
Porous asphalt—4 inches
Choker course—1.5 inch
Reservoir course—varies depending on storage requirement
Sand treatment layer—4 inches

<u>SUSTAIN Dimensions Screen</u>

Length and width based on land cover case:

Parking lots—8 ft width by 22 ft length (176 square ft) per parking space plus 20 ft wide aisles
Sidewalks—Commercial-6 ft along all four sides; residential-4 ft along front
Driveways—20 ft wide by 30 ft long

Weir height—0.01 ft

SUSTAIN Substrate Properties Screen

Depth of soil is treated as depth of all porous pavement layers above native material.

Basic porous pavement model: Porous concrete—15 inches

Porous asphalt—14 inches

Alternative porous pavement model: Varies according to reservoir course depth

Soil porosity is treated as porosity of all porous pavement layers above native material, weighted according to their depth. Porosity varies among asphalt and concrete mixes and sand and gravel selected for sublayers. Porous asphalt and concrete porosity was assumed to be 0.22, and sand or gravel base porosity was assumed to be 0.35. Use as weighted porosity:

Basic porous pavement model: Porous concrete—0.31

Porous asphalt—0.31

Alternative porous pavement model: Varies according to reservoir course depth; use the equations—

$$Overall\ Concrete\ Porosity = \sum(Component\ depth_i \text{*Component porosity}_i)\text{/Total depth}$$

Use component depths above, and for component porosities use:

Porous concrete—0.22
Porous asphalt—0.22
Choker course—0.30
Reservoir course—0.35
Sand treatment layer—0.35

Soil field capacity and **wilting point** are not applicable to porous pavements, but a handy calculator for soils in vegetative BMPs can be found at http://soil-calculator.irrigationbc.com/.

Initial surface water depth = 0

Initial moisture content = 0

Saturated soil infiltration rate:

Outwash—assumed limited to 2 inches/hour by geotextile

Till (excluding Hydrologic Soil Group D soils)—assumed naturally at least 0.5 inch/hour or amended to provide at least that rate

Hydrologic Soil Group D soils—0 (build porous pavement only with underdrain)

ET multiplier: 0 for porous pavement

Storage depth, **media void fraction**, and **background infiltration rate**: These variables apply only to a system with an underdrain. If porous pavement is considered on a D soil, assume the underdrain lies on the native soil at the bed of the reservoir course. Assume the storage depth is the diameter of the underdrain (3 inches), the void fraction is the porosity of the reservoir (0.35), and the background infiltration rate is 0.

<u>SUSTAIN Infiltration Parameters Screen</u>

There is no consensus in the literature among the Green-Ampt, Holtan, and Horton models for ability to predict measured infiltration. The Holtan model applies to vegetative systems but can be used for porous pavements by "turning off" the vegetative parameters. Doing so makes it the easiest model to use, since no other parameter assignments are needed. Set the **Vegetative parameter A** and each **Monthly growth index** = 1.

The Green-Ampt model is the second easiest to use, requiring selecting two parameters. The SUSTAIN manual recommends, as conservative values, **Suction head** = 3 inches and **Initial deficit** = 0.25.

<u>SUSTAIN Water Quality Parameters Screen</u>

Decay factor: It appears that Herrera is using 0.03/hour for TSS removal in porous pavements and is not using the Kadlec and Knight method.

<u>SUSTAIN Cost Factors Screen</u>

Herrera is currently reporting construction costs for porous asphalt as \$20/ft^2 on outwash soil and \$19/ft^2 on till.[25] Herrera (2011)[26] gave an average of \$13.90/ft^2 for construction (usually, including design) of porous concrete and asphalt systems, working from the Puget Sound database. A single source reported an O&M cost of \$0.02/ft^2 (presumably, annually). These costs are not out of line with those reported in a survey of other sources:

http://www.crwa.org/projects/bmpfactsheets/crwa_permeable_pavement.pdf

http://www.projectcleanwater.org/pdf/lid/Permeable_Pavements.pdf

http://ntl.bts.gov/lib/43000/43500/43570/TSR-2011-permeable-pavements.pdf

www.region9wv.com/Bay/Calculators/**Permeable_Pavement**.xls

http://www.saveitlancaster.com/wp-content/uploads/2011/10/07_PorousPavement.pdf

www.lowimpactdevelopment.org/.../3-2_**permeablepavement**_draft.doc

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[25] Federal Way *SUSTAIN* Model Draft Optimization Approach

[26] Herrera Environmental Consultants. 2011. Puget Sound Stormwater BMP Cost Database (Draft). Prepared for Washington Department of Ecology, Olympia, WA.

APPENDIX B

O&M Investigation

INVESTIGATION OF OPERATION AND MAINTENANCE COST COMPONENTS FOR GREEN STORMWATER INFRASTUCTURE

By Richard Horner
March 15, 2013

Question

Do operation and maintenance (O & M) costs for green stormwater infrastructure (GSI) practices reported in the "WRIA 9 Stormwater Retrofit BMP Cost Assumptions (12/13/2012)" memorandum include indirect expenses such inspection, enforcement, documentation, and record keeping, as well as the direct costs of performing the maintenance work? If not, what amounts should be added to the costs reported for rain barrels, cisterns, rain gardens (also known as bioretention cells), biofiltration swales, and porous pavements to cover indirect expenses?

Background

The trend in the stormwater management field is toward the use of more smaller, widely distributed GSI practices closer to runoff sources and less larger, centralized conventional facilities located down-gradient and separated from sources. The latter facilities are often on public property and easily accessible to stormwater agency staff for O & M functions, whereas many of the decentralized practices will be established on private property. Agency staff are concerned that in this situation access will be more difficult and time-consuming, and thus more demanding on budgets. Access could be restricted by such circumstances as lack of right of entry, fencing and locked gates, and threatening dogs.

The WRIA 9 Stormwater Retrofit project is applying the SUSTAIN model to select retrofit strategies based on cost-effectiveness optimization relative to meeting designated biological and water quality targets in receiving waters. Early model runs showed certain GSI options to be important components of optimum strategies. However, if the O & M cost inputs to the model are not all-inclusive, these results could be misleading. It is, hence, important to make sure the costs are realistic, both to get reliable model output and to provide a foundation for realistic agency budgeting.

"WRIA 9 Stormwater Retrofit BMP Cost Assumptions (12/13/2012)" Memorandum Data

- Rain barrels and cisterns—These BMPs were assumed to be on private property normally. O & M costs were considered to be negligible, presumably because these simple devices would not be subject to the usual demands of stormwater unit maintenance, like sediment removal, replacing vegetation or filter media, etc. In any event, maintenance or replacement would be a private responsibility. If these facilities are to be in the inspection system, costs must be added to represent the public agency tasks.

- Bioretention—The memorandum anticipated two types of bioretention units, a cellular "rain garden", most often on private land, and a linear form on public road right of way. The latter type is equivalent to a conventional biofiltration swale, but with soil amendment if needed to boost performance on less favorable soils. An O & M cost of \$1.10 ft^{-2} yr^{-1} was assigned to both, mostly borne by private owners of rain gardens and public agencies for roadside swales.

- Porous pavements—Porous asphalt or concrete pavements are being considered in the study for private parking lots and driveways. Review of available data yielded a consensus O & M cost of \$0.02 ft^{-2} yr^{-1}, a private expense under this project's scenario.

<u>Inclusiveness of "WRIA 9 Stormwater Retrofit BMP Cost Assumptions (12/13/2012)" Memorandum Data</u>

The reports reviewed to select representative O & M costs rarely, if ever, itemized the components included. There were no indications that the question raised in this memorandum regarding indirect costs was considered. The author discussed this point with John Lenth and Rebecca Dugopolski of Herrera Environmental Consultants, a key source of the data adopted for use in this project. They conducted a study with objectives similar to this project's, also using SUSTAIN, and are two of the authors of the report "SUSTAIN Modeling for Controlling Toxic Chemicals in Small Streams". These correspondents expressed the definite opinion that the O & M costs they used, and were largely adopted in this project, do not include the indirect factors.

<u>A Basis for Adding Indirect O & M Costs</u>

Dave Hancock of King County Stormwater Services Section has been developing "Flow Control Best Management Practices Protocols", with GSI practices included. He provided the author extensive insights on aspects of this memorandum's question based on his experience and professional judgment. He is anticipating that 2 hours will be needed for routine inspection of relatively small GSI facilities, including administration before and after the inspection and documentation and record keeping, but not repeat visits or enforcement if necessary.

Dave estimated the need for return visits, also taking 2 hours each, at no more than 10 percent of the cases. He further judged that the enforcement rate would run somewhat higher, about 15 percent, and would typically take 16 hours.

He recommended considering inspection frequencies of every year for porous pavements, every 2 years for rain gardens and biofiltration swales, and every 5 years for cisterns and rain barrels. Finally, he quoted labor rates of about \$80-85/hour for inspections and \$90-100 for enforcements.

The Project Management Team debated the subject at its meeting on March 6, 2013 and generally endorsed the proposed approach. However, the group recommended a distinction between private bioretention (rain gardens in the project's conception) and the public form of bioretention (roadside swales), with the former being inspected every two years and the latter each year.

This information provides a basis for adding indirect O & M expenses to the direct costs documented in the "WRIA 9 Stormwater Retrofit BMP Cost Assumptions (12/13/2012)" memorandum, as follows. Both components are annualized; but the direct costs are on a footprint basis (per ft^2 of surface), while the indirect costs would be per individual unit.

- Rain barrels and cisterns—Indirect cost = (2 hours/unit inspection) x (1 unit inspection/5 years) x (1.1 multiplier for repeat inspections) x ($85/hour) + (16 hours/enforcement) x (1 potential enforcement/5 years) x (0.15 multiplier for expected enforcement frequency) x ($100/hour) = $85.40 $unit^{-1}$ yr^{-1}

- Private bioretention (rain gardens)—Indirect cost = (2 hours/unit inspection) x (1 unit inspection/2 years) x (1.1 multiplier for repeat inspections) x ($85/hour) + (16 hours/enforcement) x (1 potential enforcement/2 years) x (0.15 multiplier for expected enforcement frequency) x ($100/hour) = $213.50 $unit^{-1}$ yr^{-1}

- Public bioretention (biofiltration swales)[1]—Indirect cost = (2 hours/unit inspection) x (1 unit inspection/2 years) x ($85/hour) = $170.00 $unit^{-1}$ yr^{-1}

- Porous pavements—Indirect cost = (2 hours/unit inspection) x (1 unit inspection/1 year) x (1.1 multiplier for repeat inspections) x ($85/hour) + (16 hours/enforcement) x (1 potential enforcement/1 year) x (0.15 multiplier for expected enforcement frequency) x ($100/hour) = $427.00 $unit^{-1}$ yr^{-1}

<u>O & M Cost Summary</u>

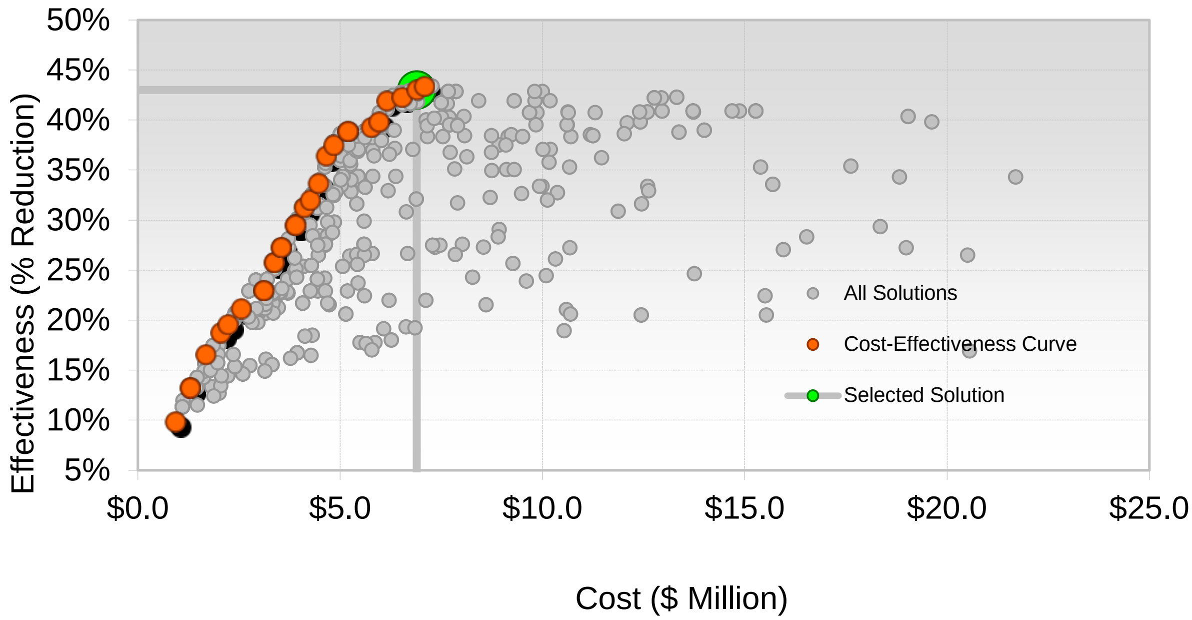
Unit	Direct Cost (ft^{-2} yr^{-1})	Indirect Cost ($unit^{-1}$ yr^{-1})
Rain barrels and cisterns	~$0[a]	$85.40[b]
Private Rain gardens	$1.10[c]	$213.50[b]
Public biofiltration swales	$1.10[b]	$170.00[b]
Porous pavements	$0.02[c]	$427.00[b]

[a] Any replacement or repairs would be a private expense.
[b] Public agency cost
[c] Private cost

[1] It is assumed that there will be no need for repeat visits or enforcement for public facilities.

APPENDIX C

Till Soils Cost-Effectiveness Curves



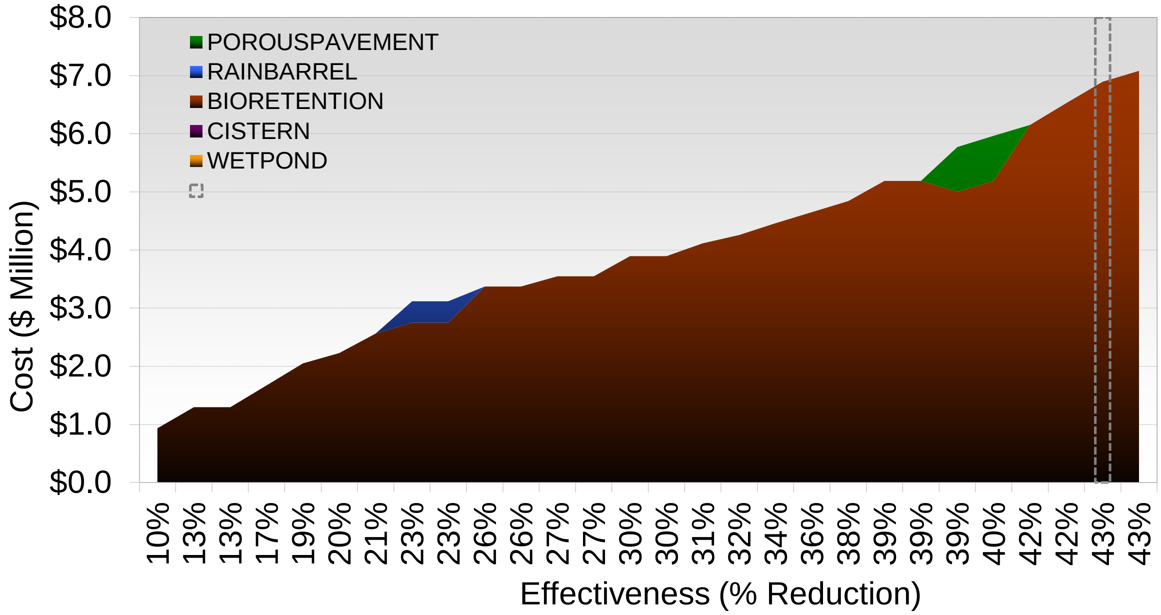
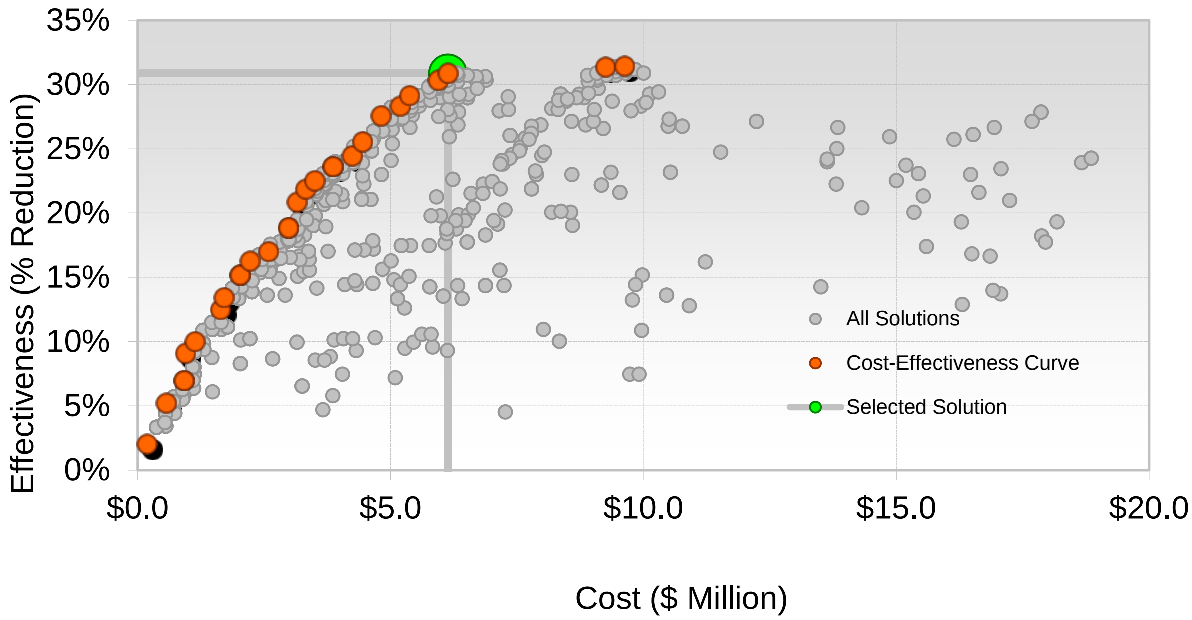


Figure 16. Figures showing cost-effectiveness results for Green only, Rain Barrel, No Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



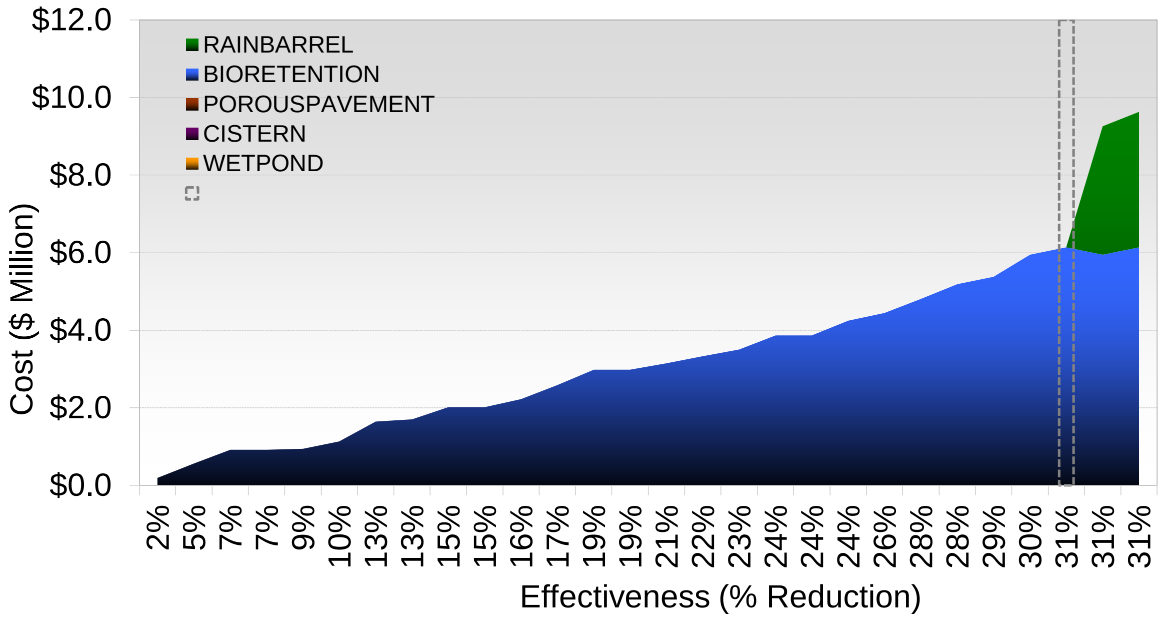
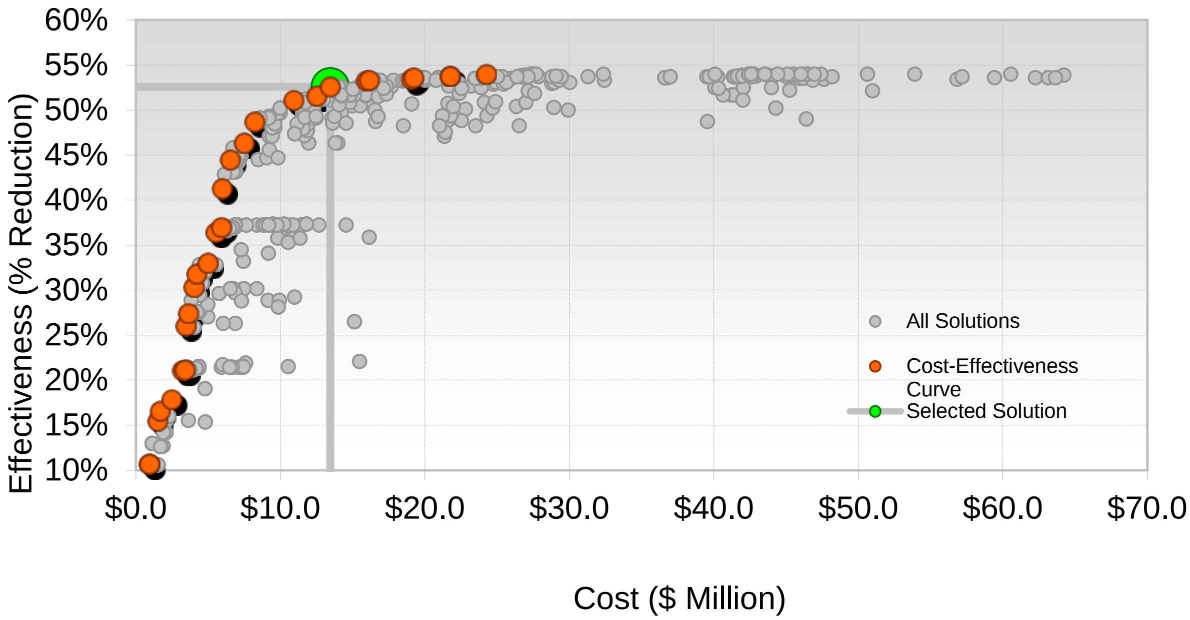


Figure 17. Figures showing cost-effectiveness results for Green only, Rain Barrel, No Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).



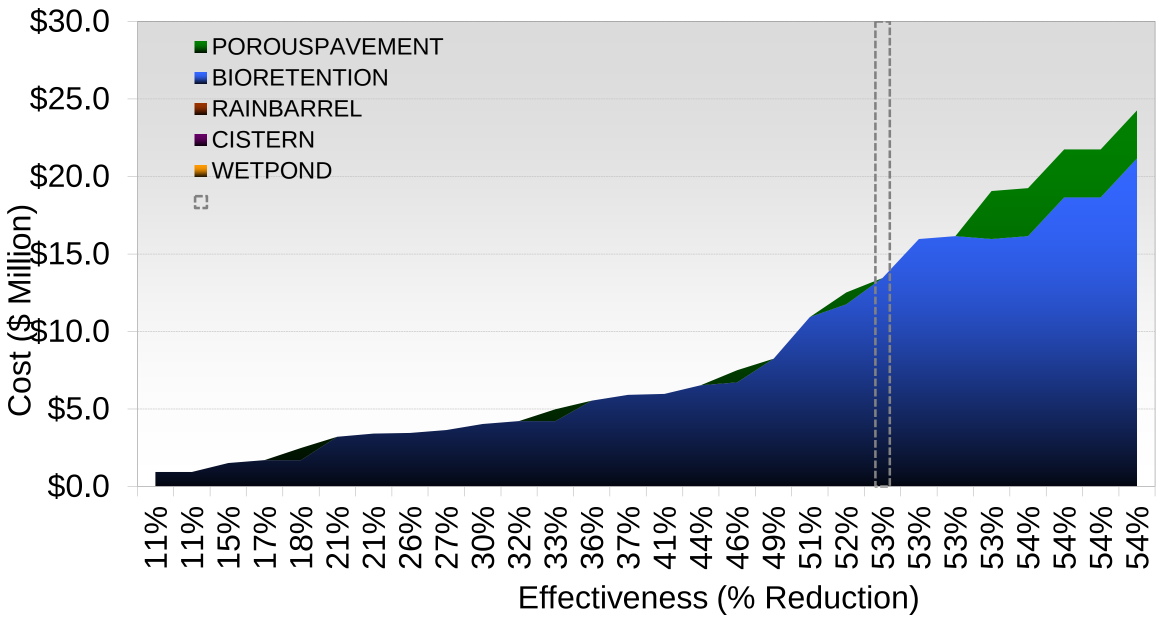
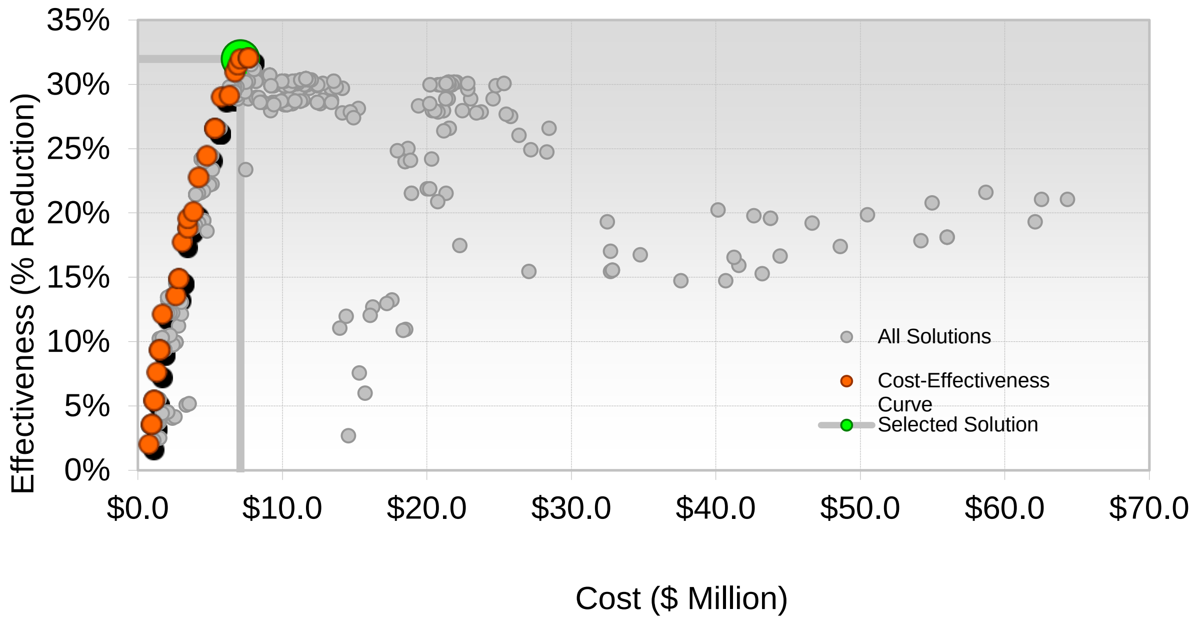


Figure 18. Figures showing cost-effectiveness results for Green only, Rain Barrel, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0/hr (Till Soils).



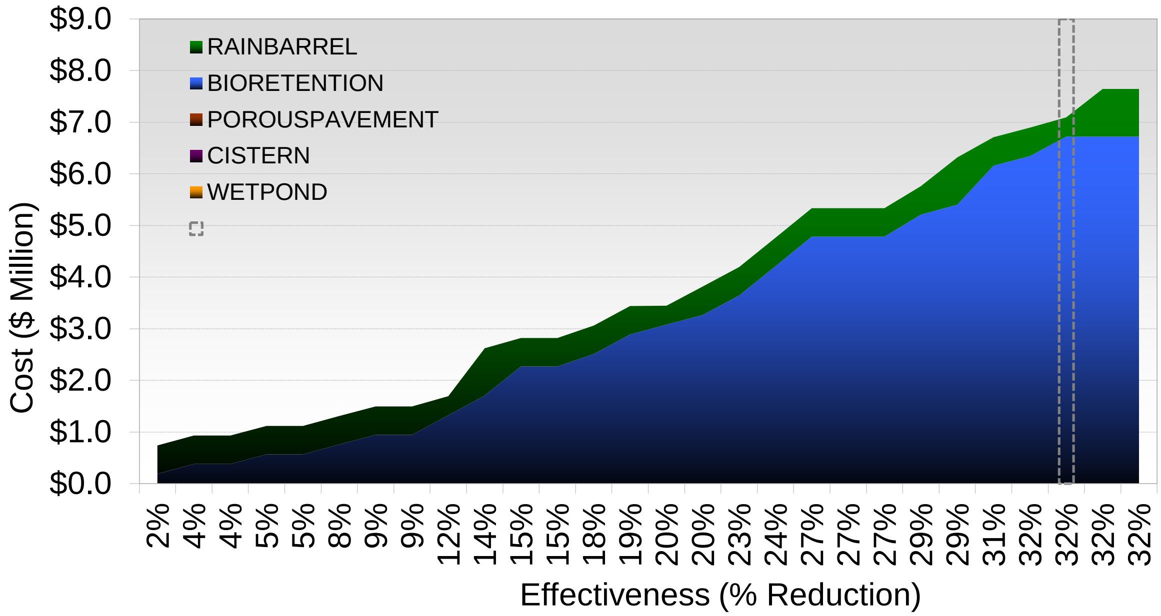
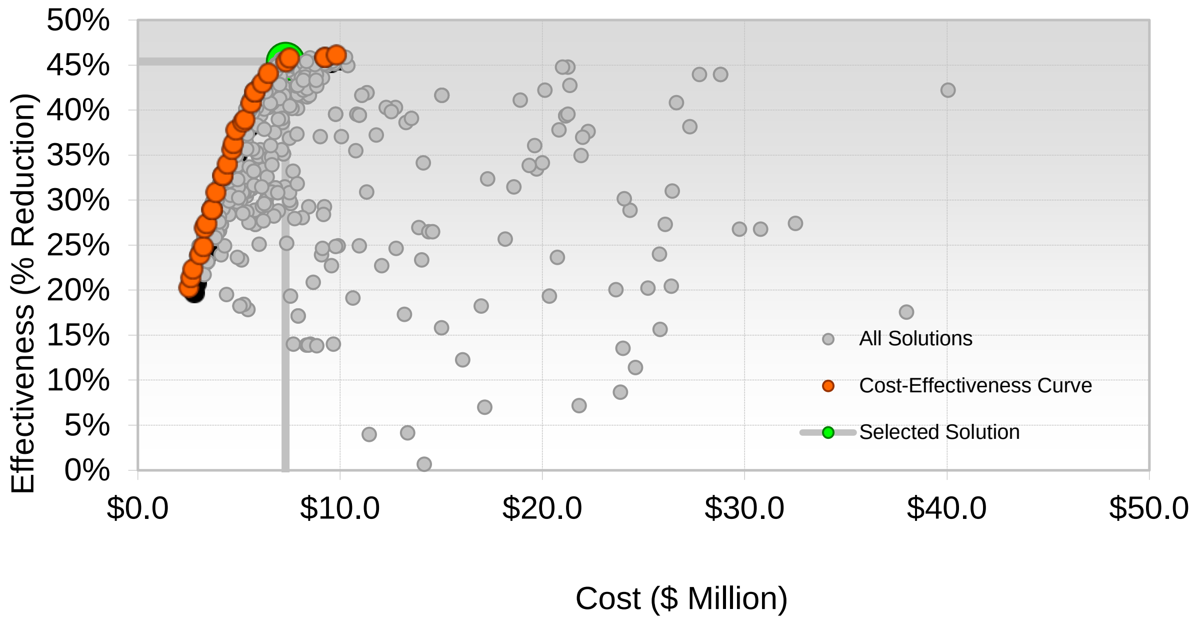


Figure 19. Figures showing cost-effectiveness results for Green only, Rain Barrel, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).



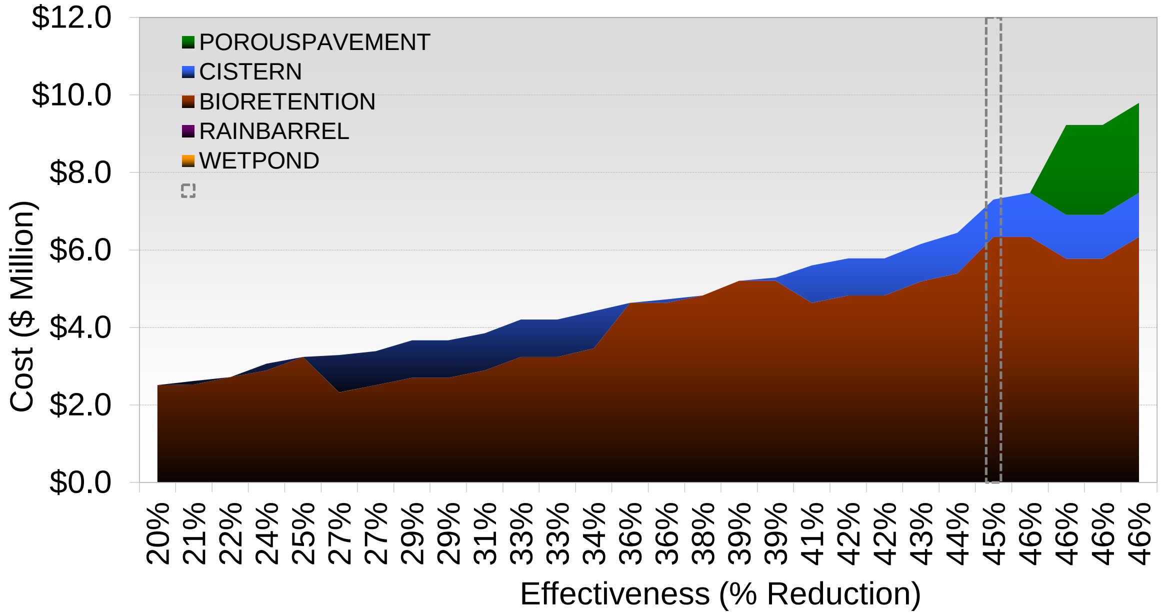
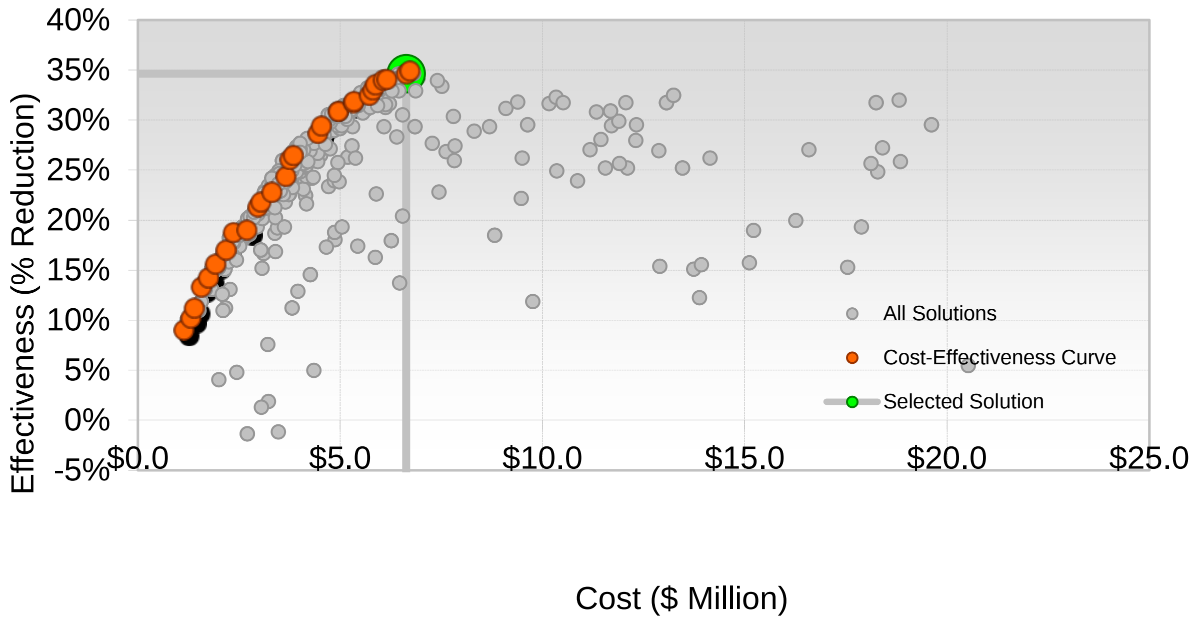


Figure 20. Figures showing cost-effectiveness results for Green only, Cistern, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



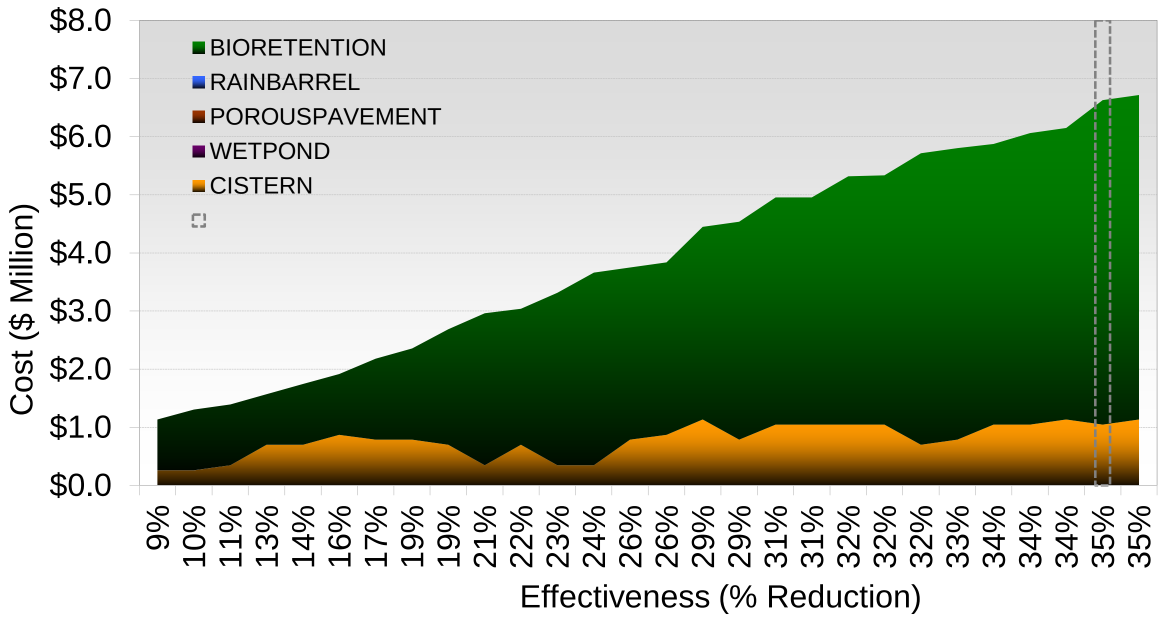
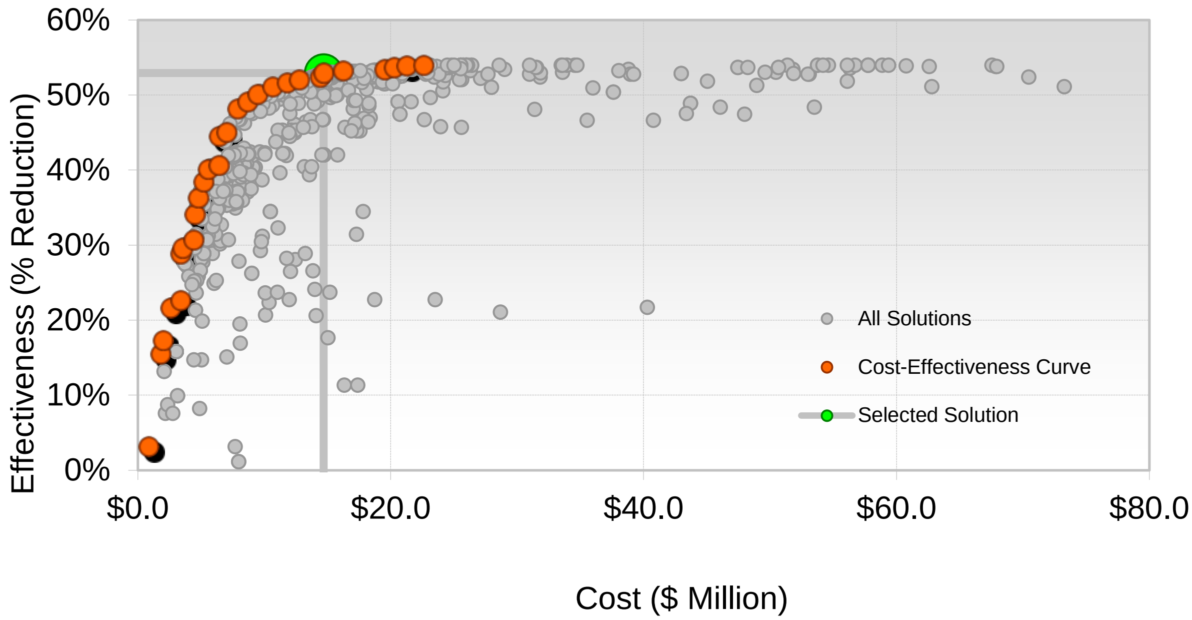


Figure 21. Figures showing cost-effectiveness results for Green only, Cistern, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).



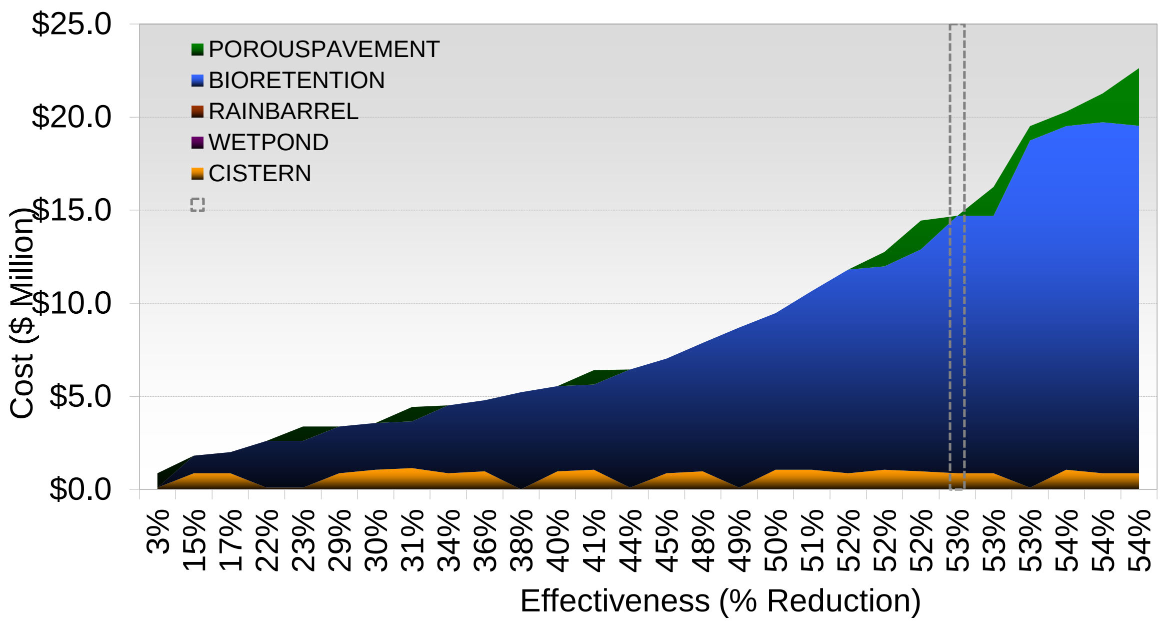
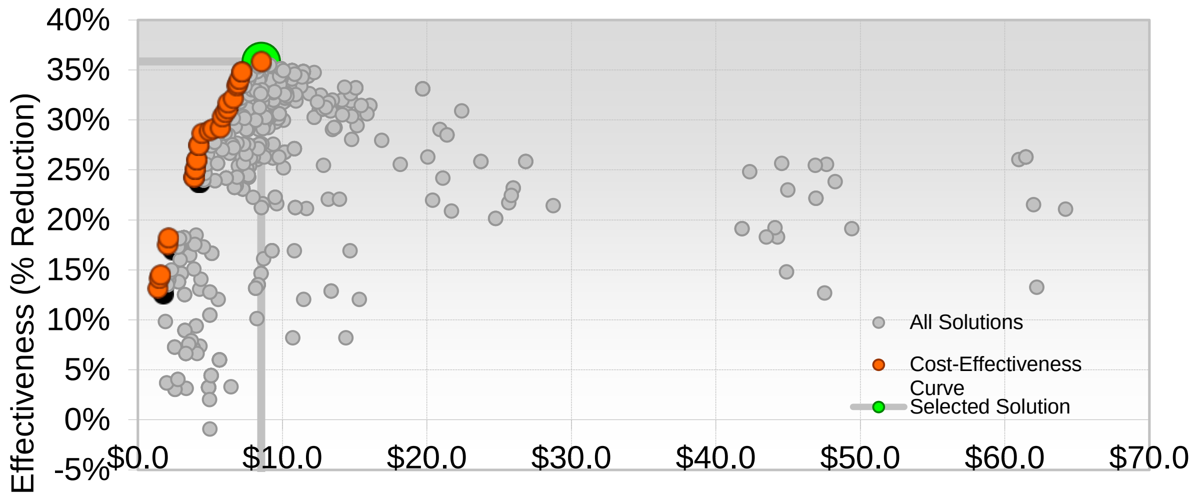


Figure 22. Figures showing cost-effectiveness results for Green only, Cistern, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



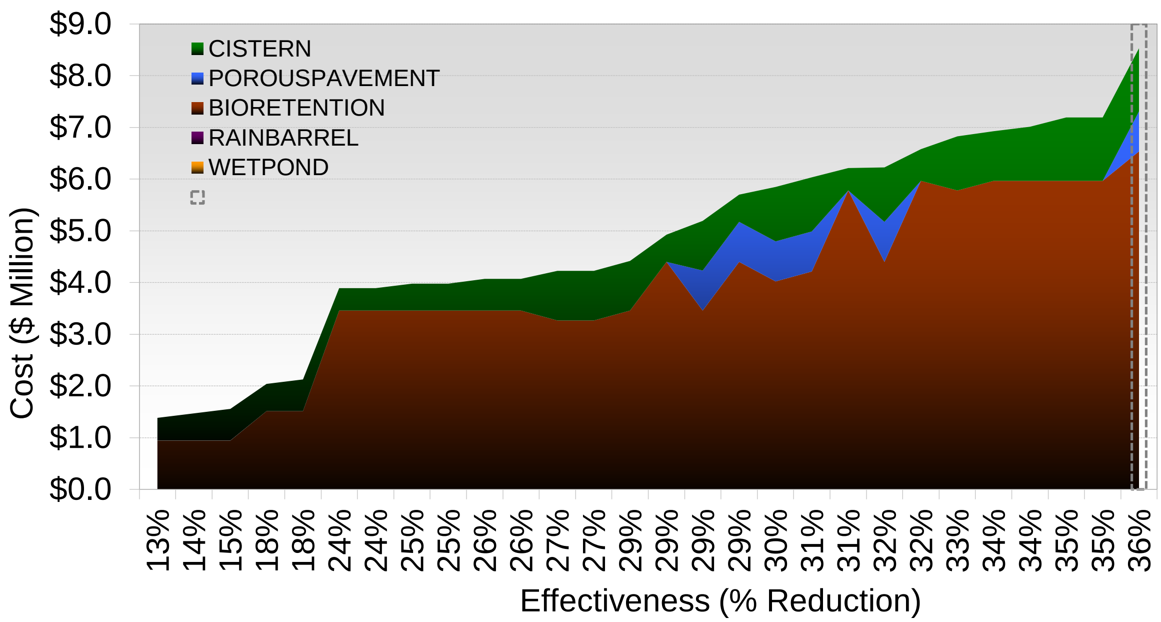


Figure 23. Figures showing cost-effectiveness results for Green only, Cistern, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).

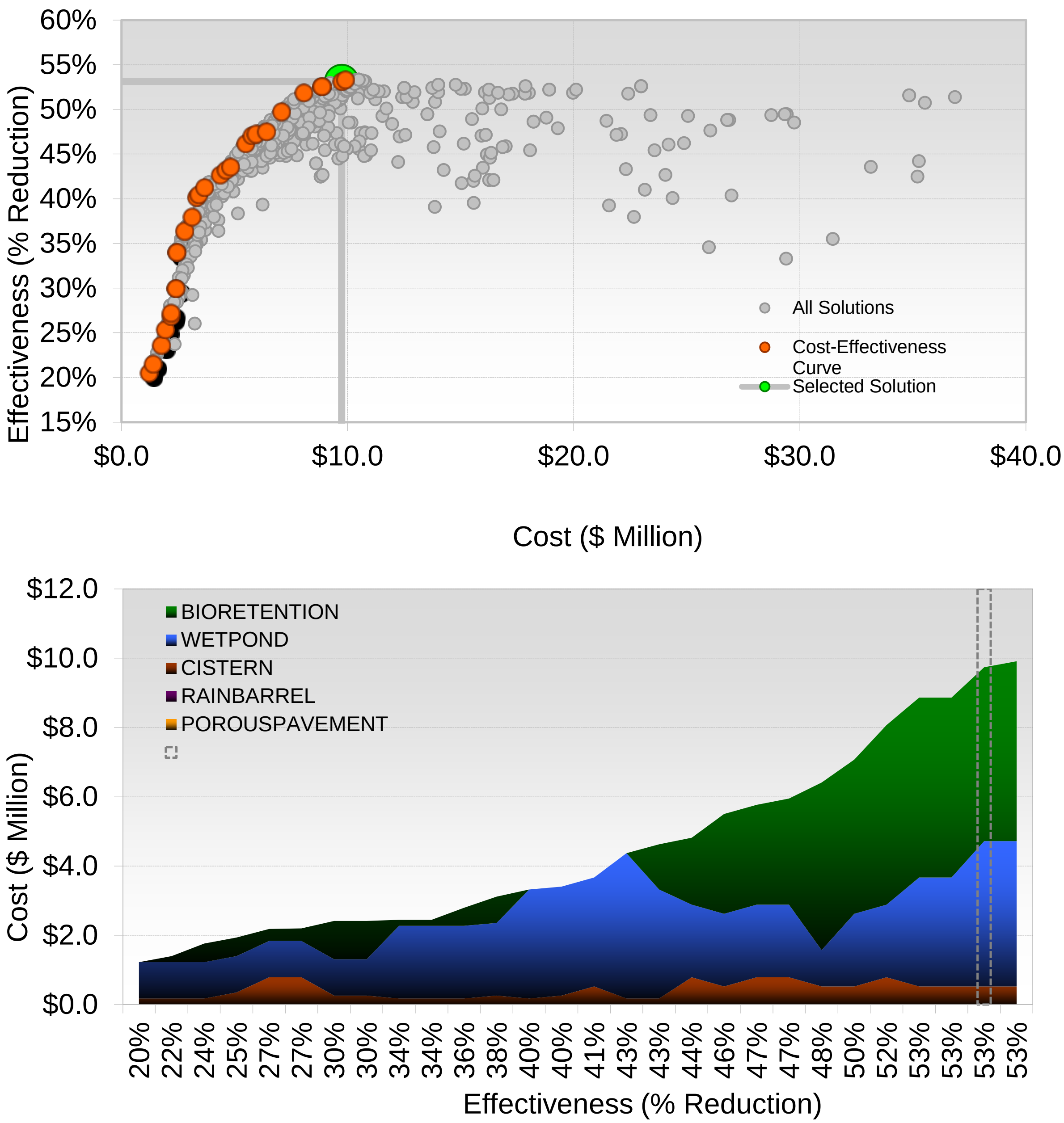
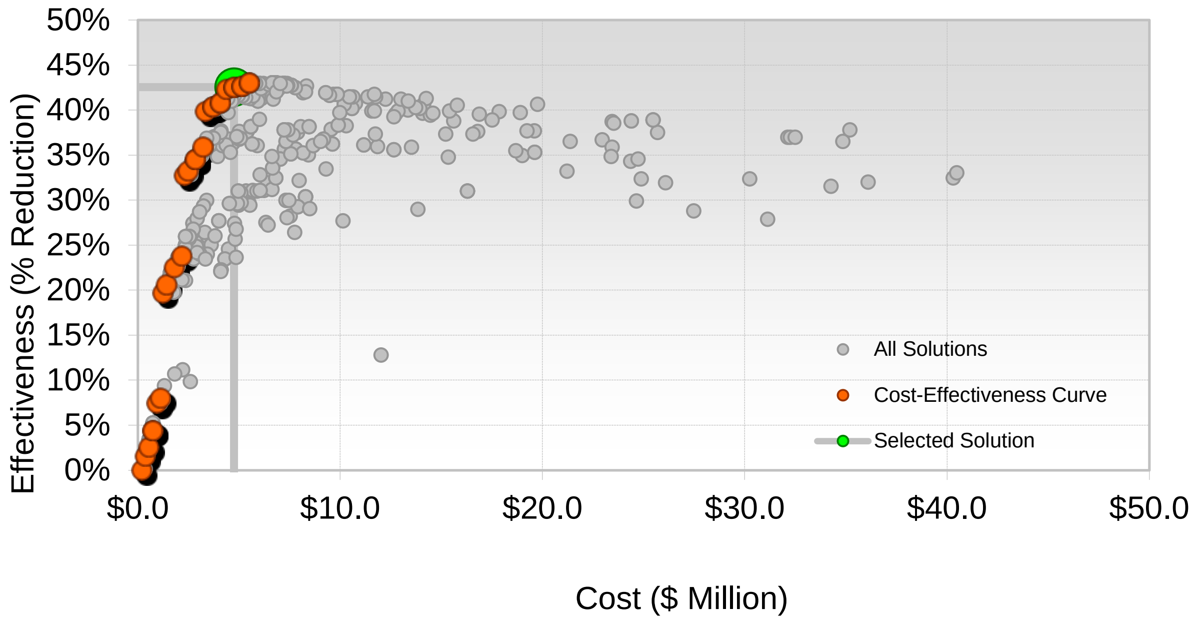


Figure 24. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



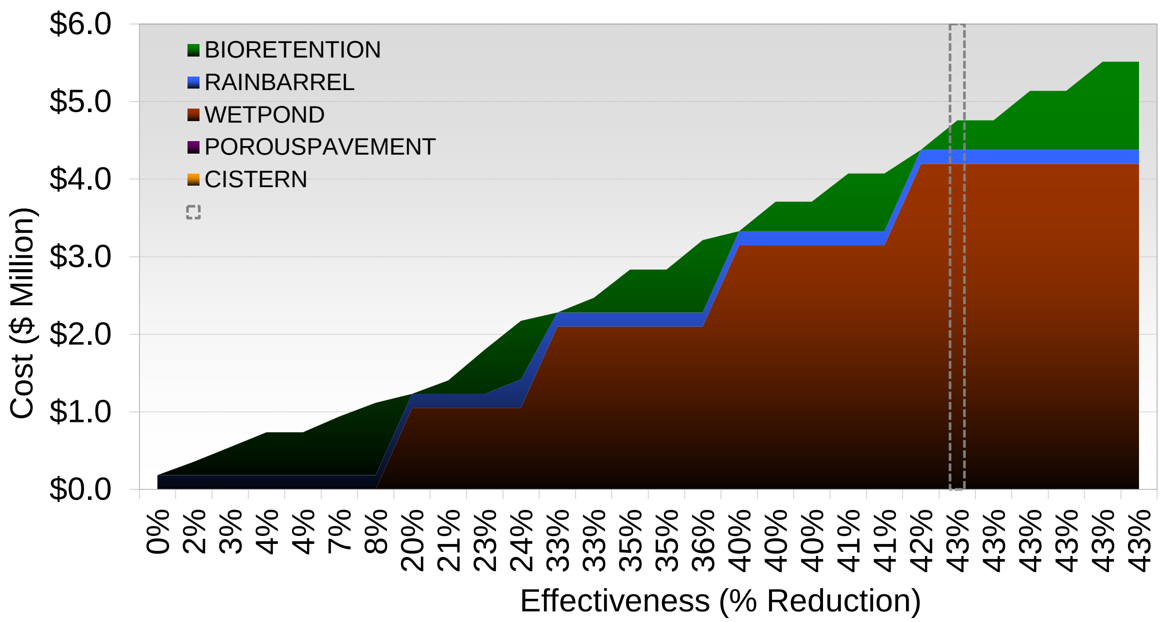
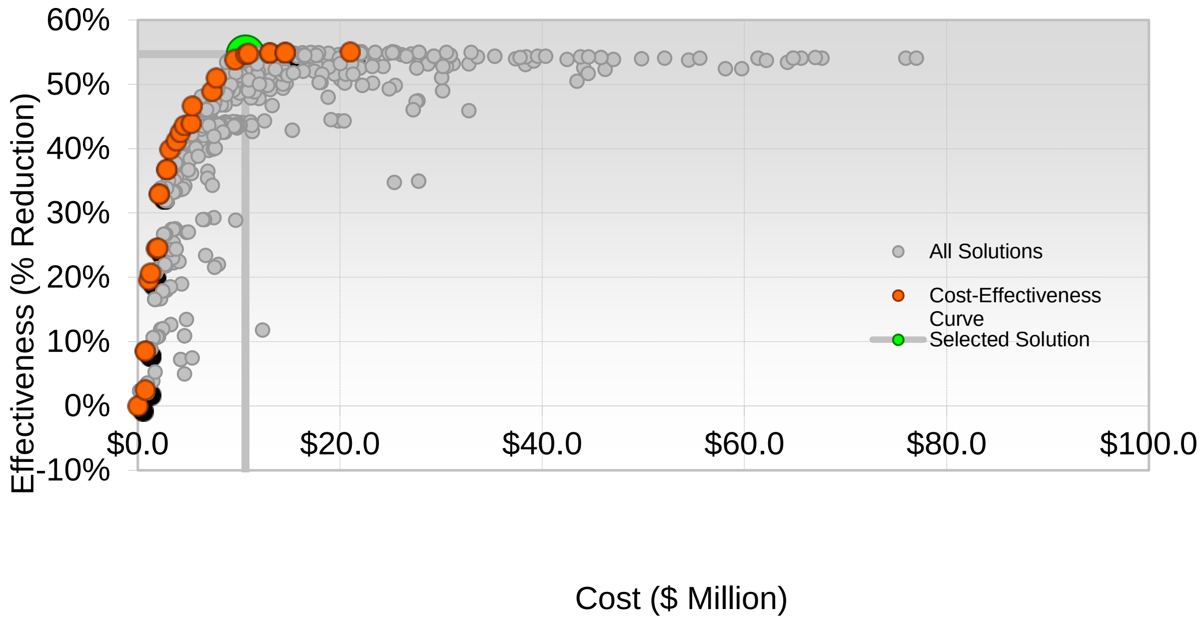


Figure 25. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).



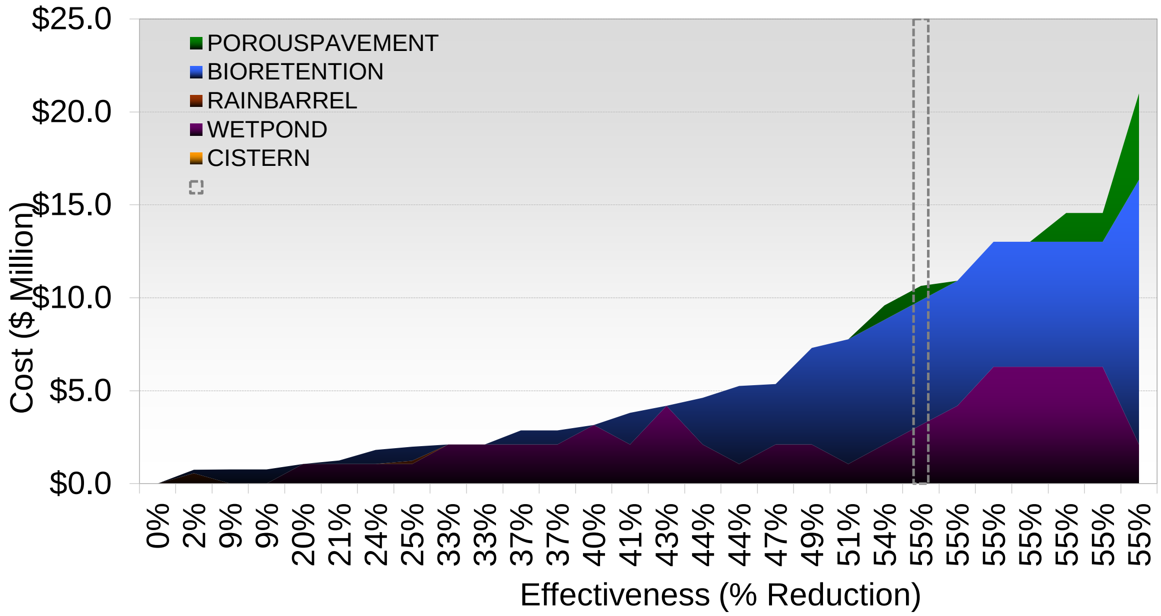
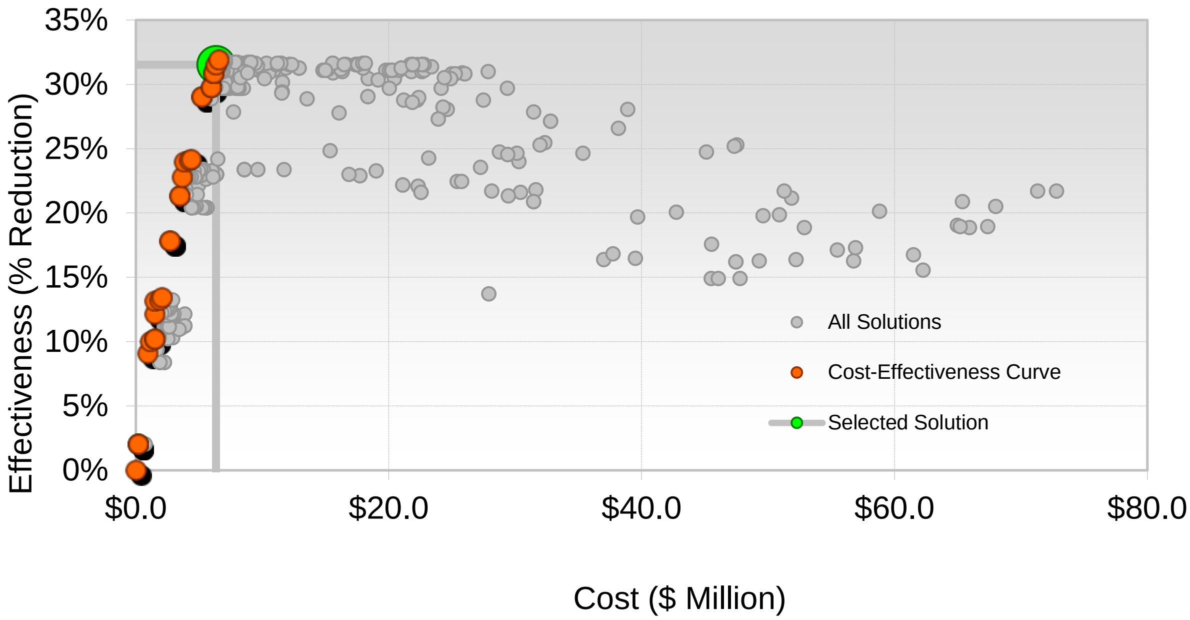


Figure 26. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



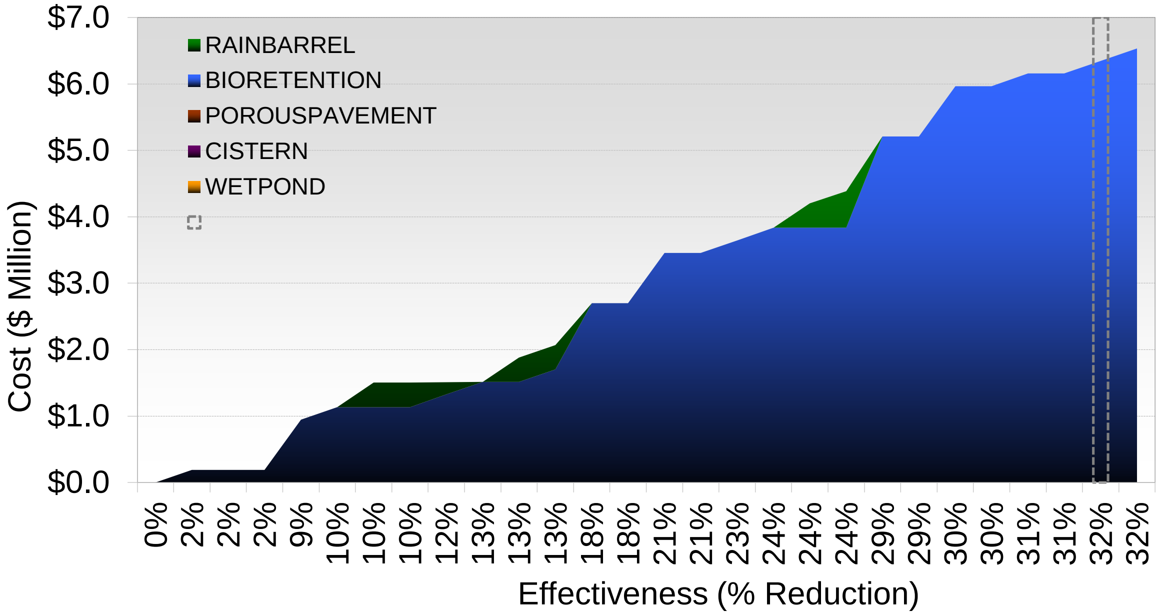


Figure 27. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils).

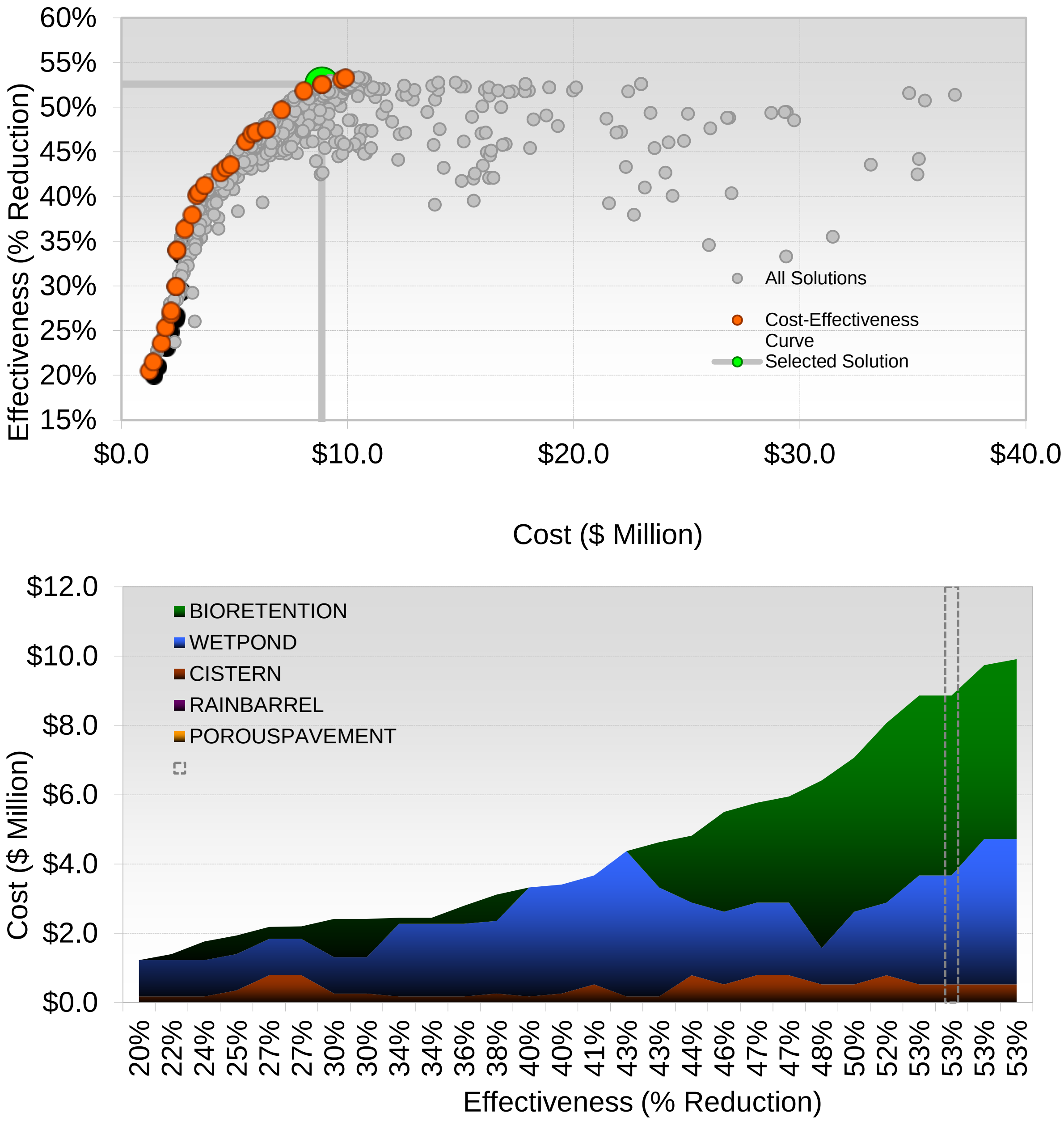
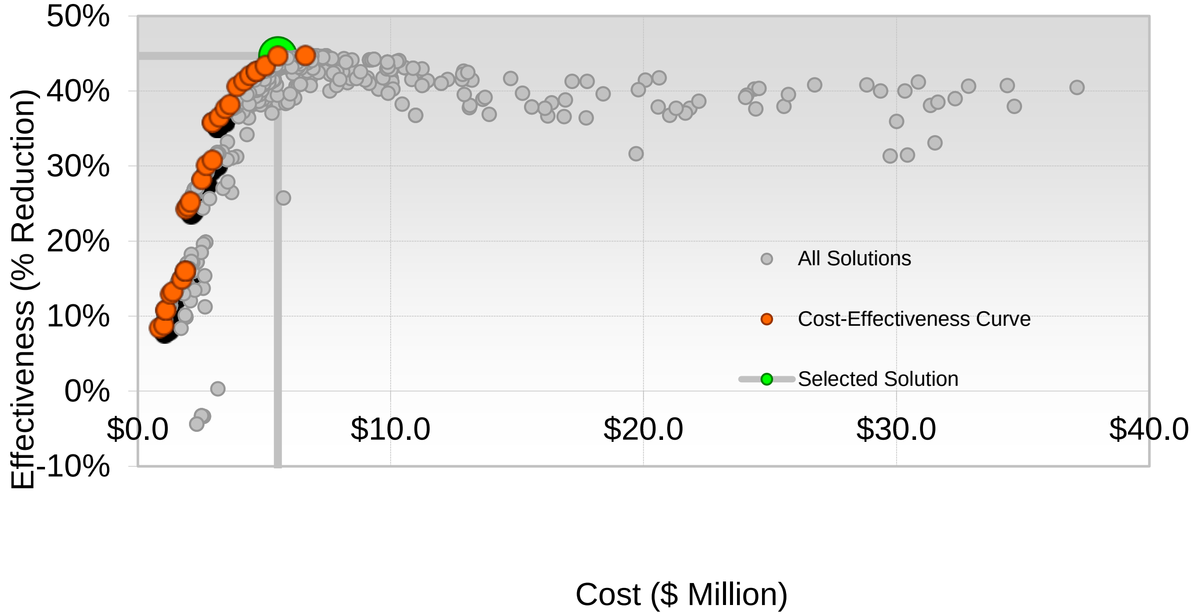


Figure 28. Figures showing cost-effectiveness results for Green+Gray, Cistern, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



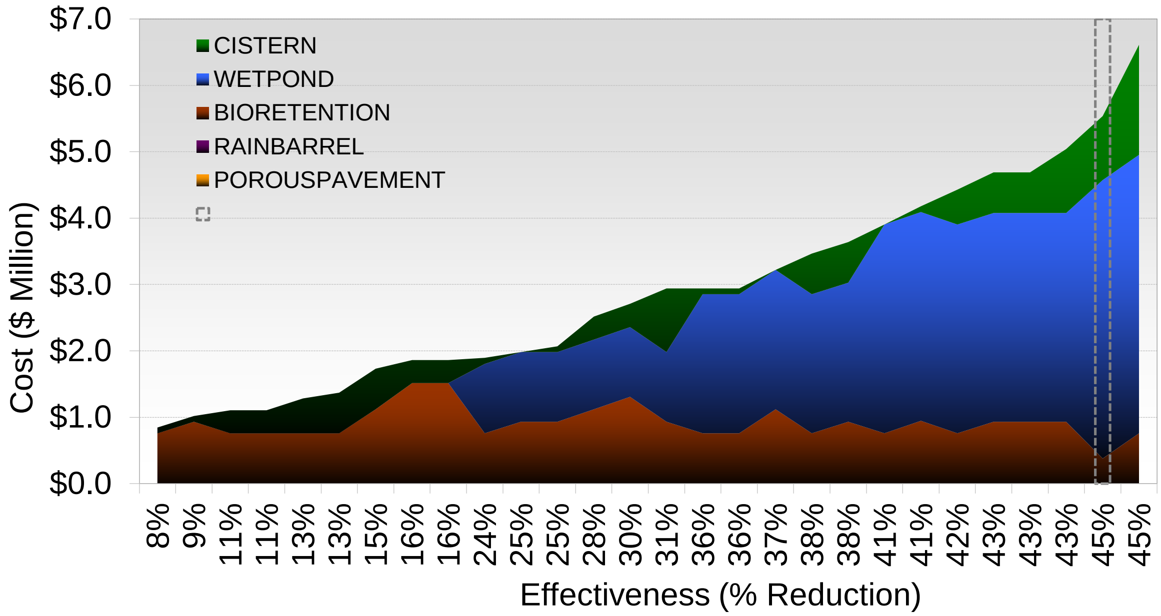
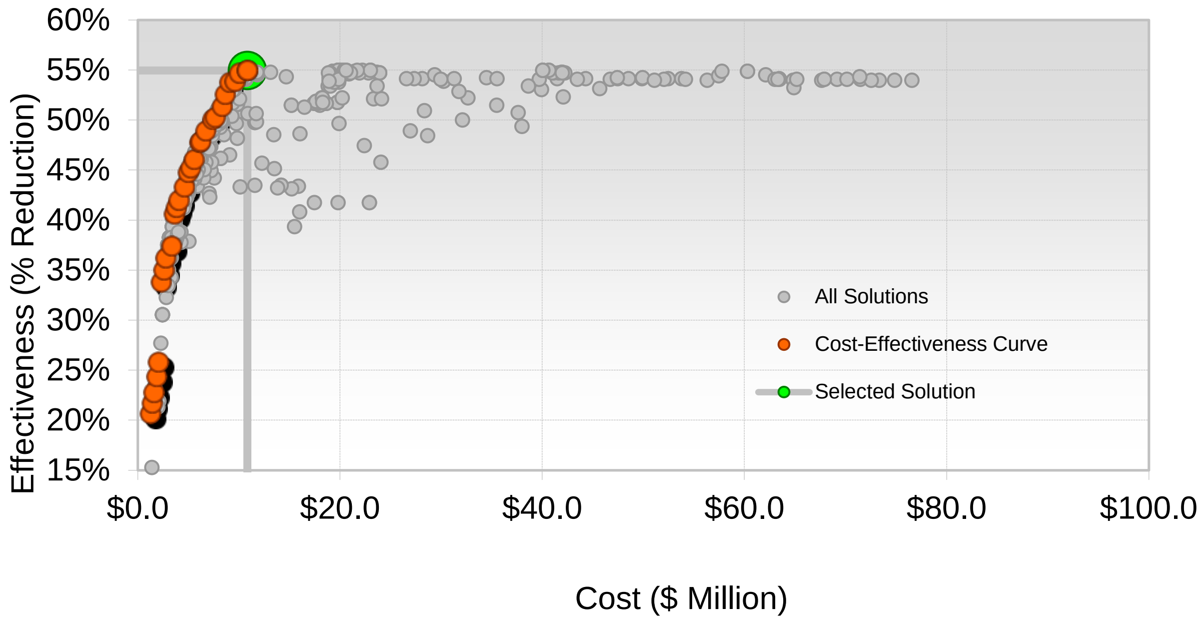


Figure 29. Figures showing cost-effectiveness results for Green+Gray, Cistern, 0% Pervious Treatment, Aquifer Recession Coefficient equal to 0.10/hr (Till Soils).



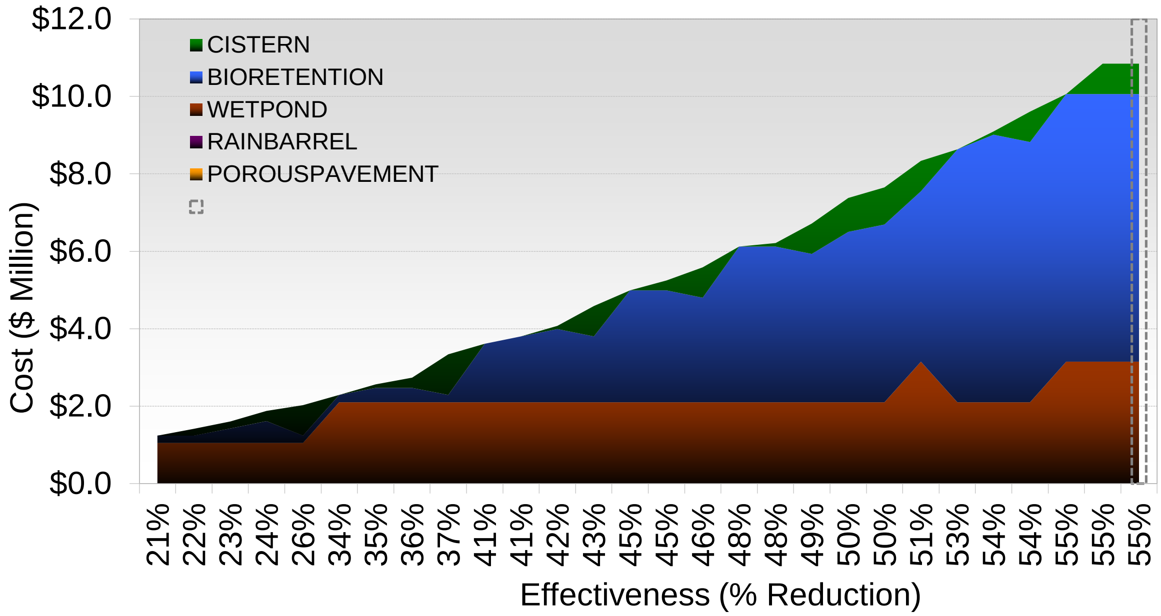
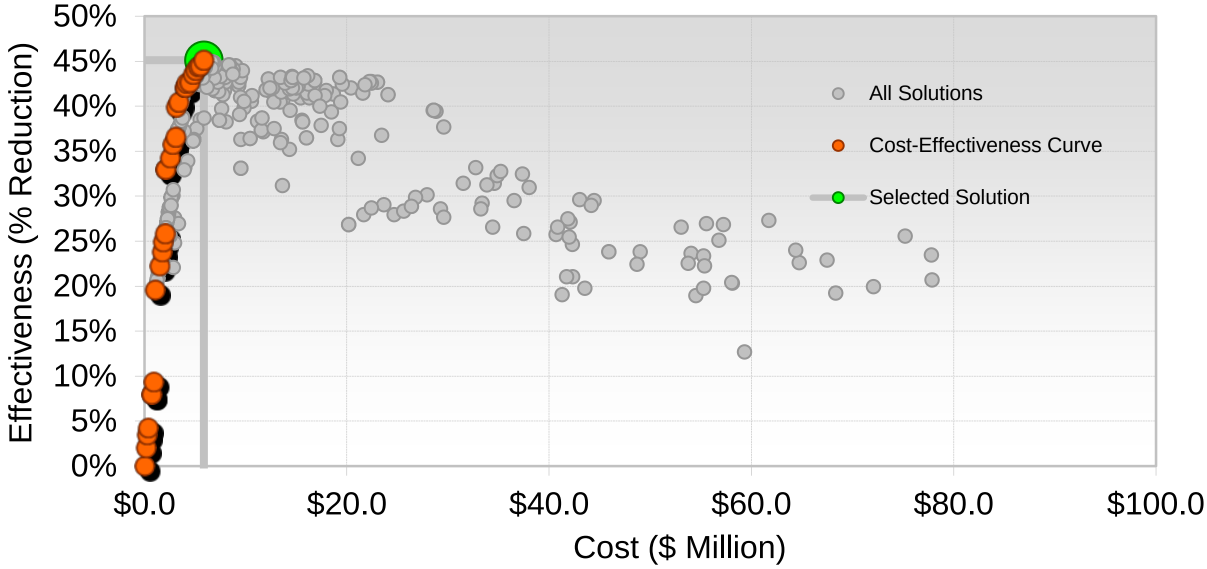


Figure 30. Figures showing cost-effectiveness results for Green+Gray, Cistern, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.0/hr (Till Soils).



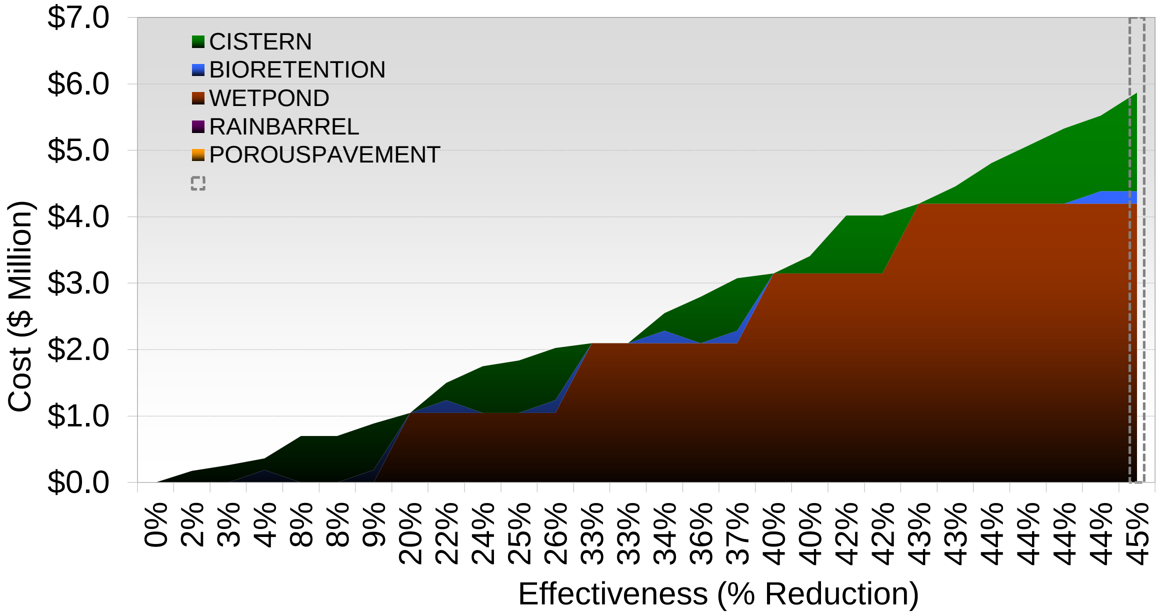
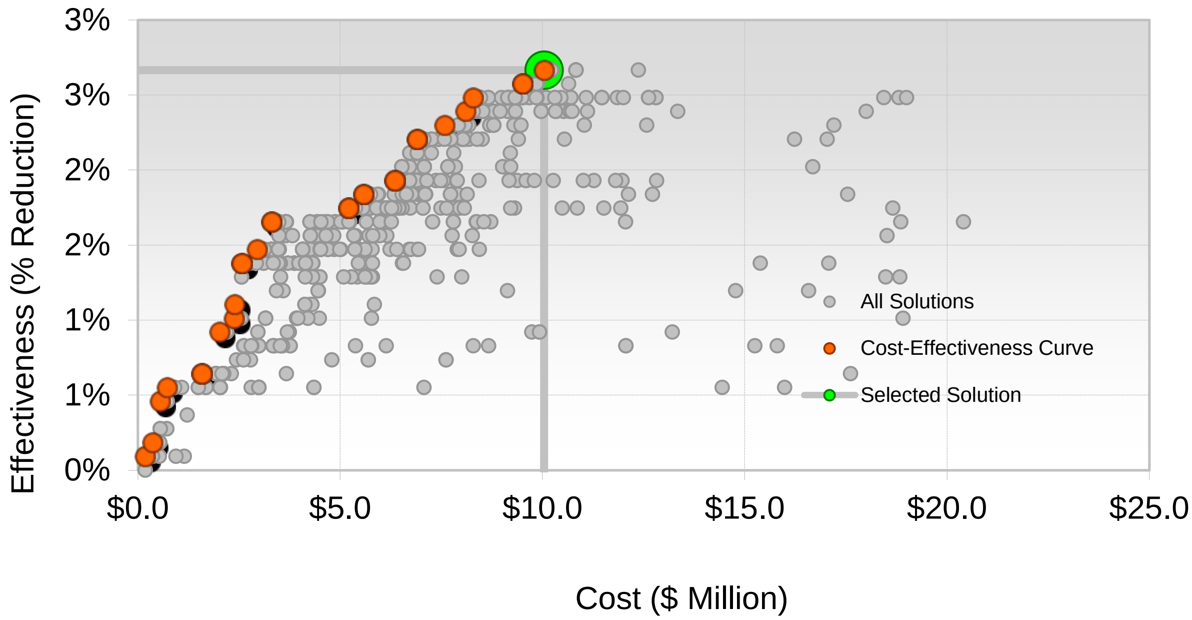


Figure 31. Figures showing cost-effectiveness results for Green+Gray, Cistern, 80% Pervious Treatment, Aquifer Recession Coefficient equal to 0.1/hr (Till Soils)

APPENDIX D

Type D Soils Cost-Effectiveness Curves



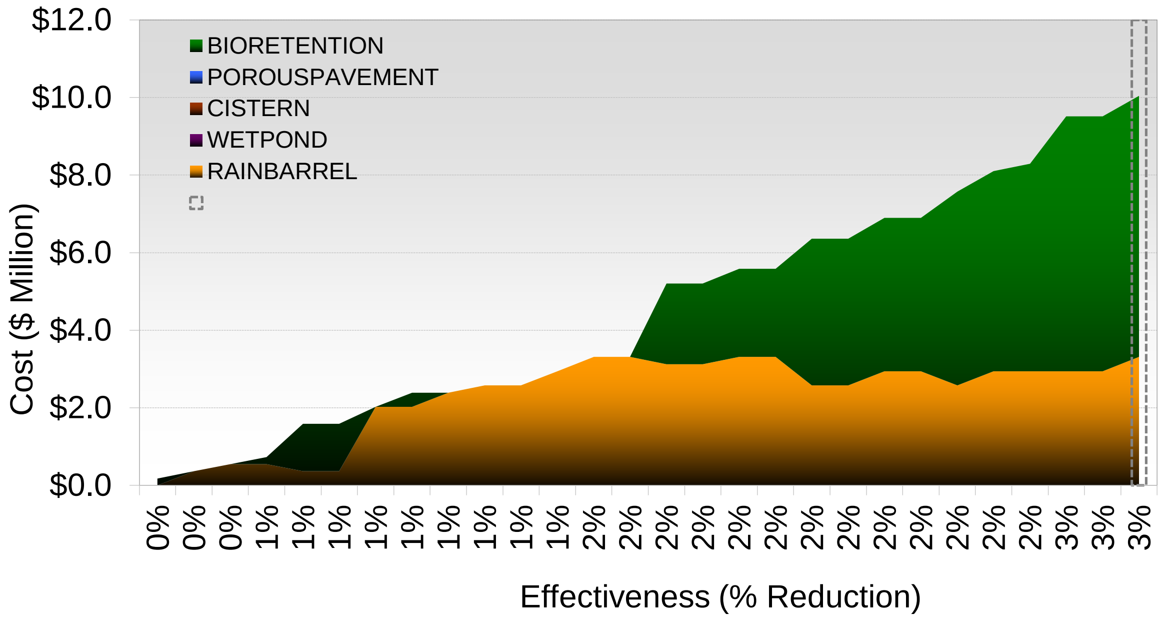
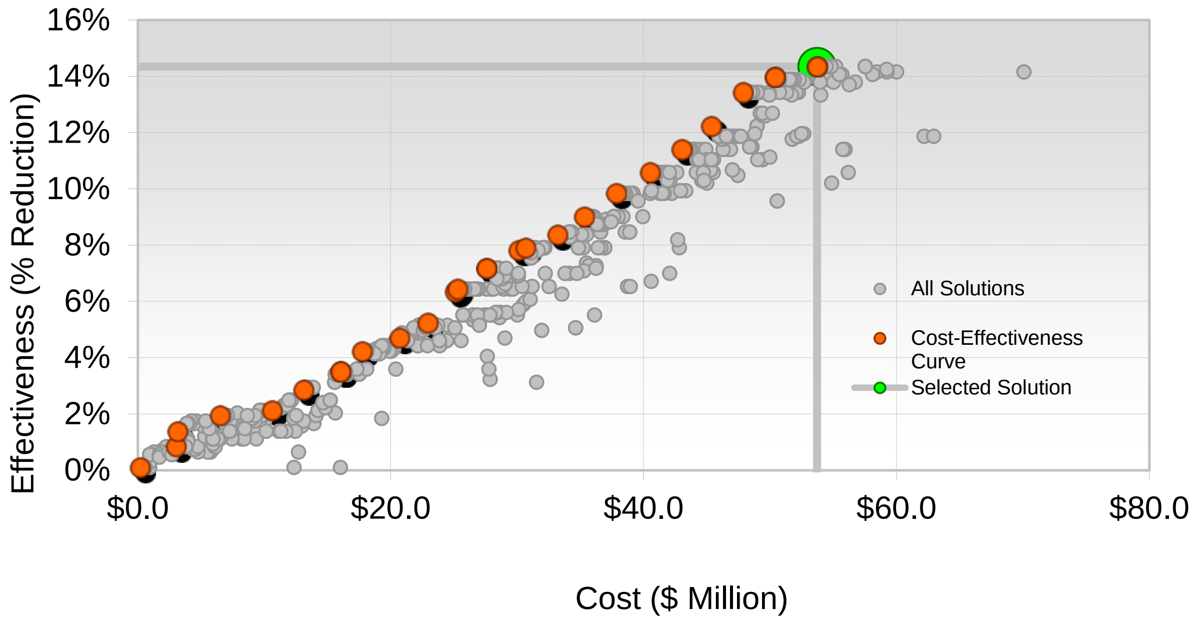


Figure 32. Figures showing cost-effectiveness results for Green only, Rain Barrel, No Pervious Treatment (Type D Soils).



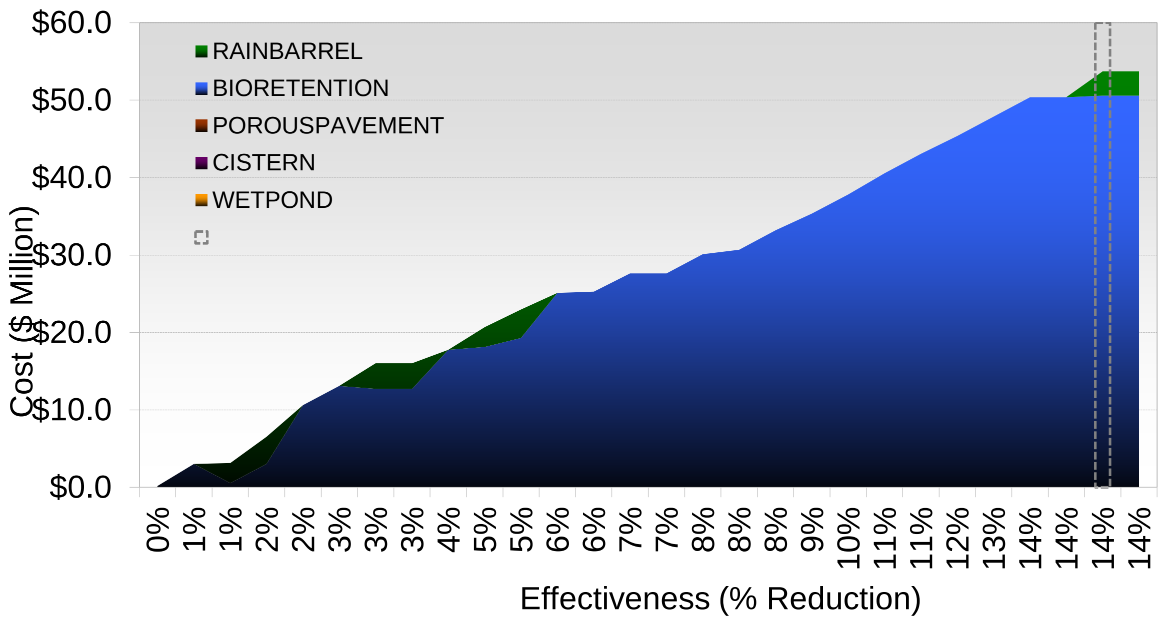
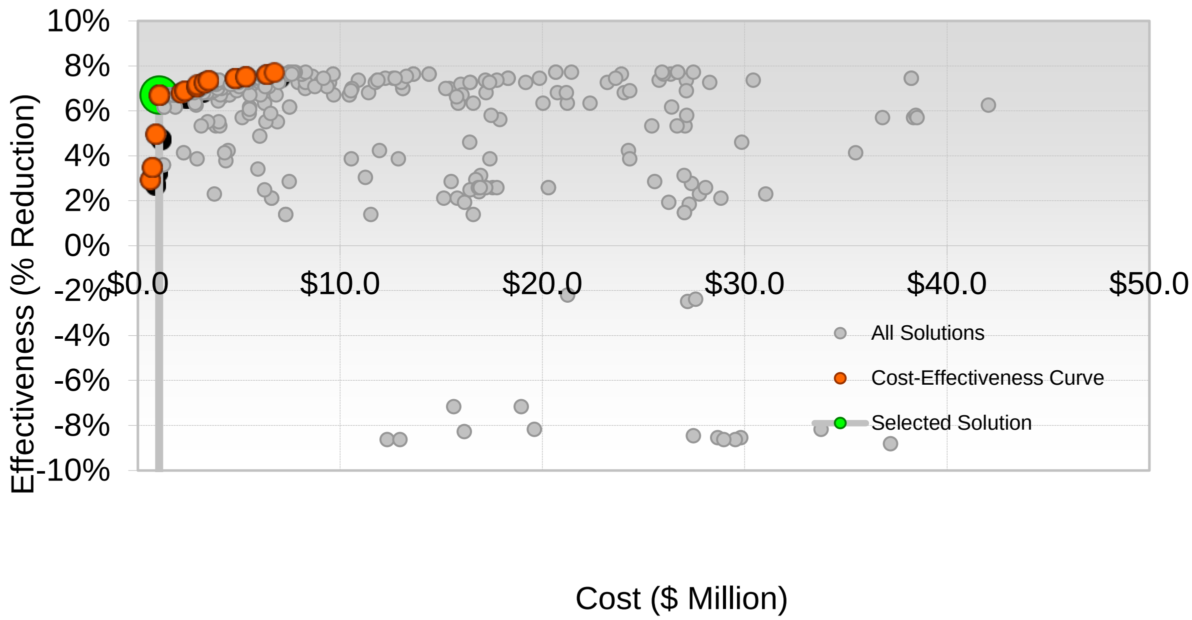


Figure 33. Figures showing cost-effectiveness results for Green only, Rain Barrel, 80% Pervious Treatment (Type D Soils).



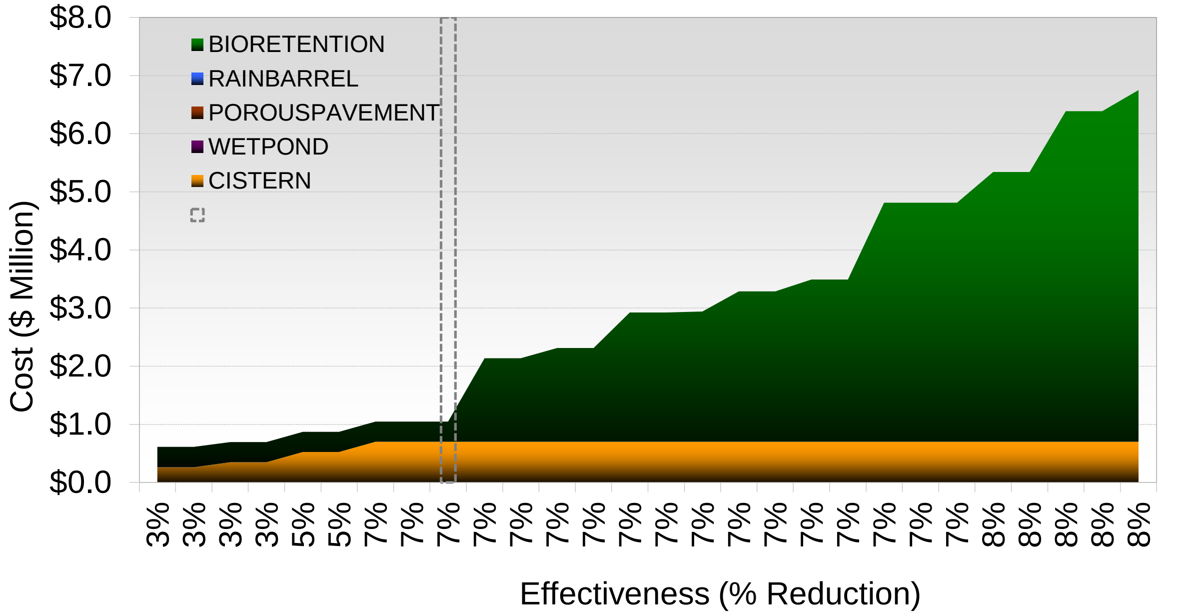
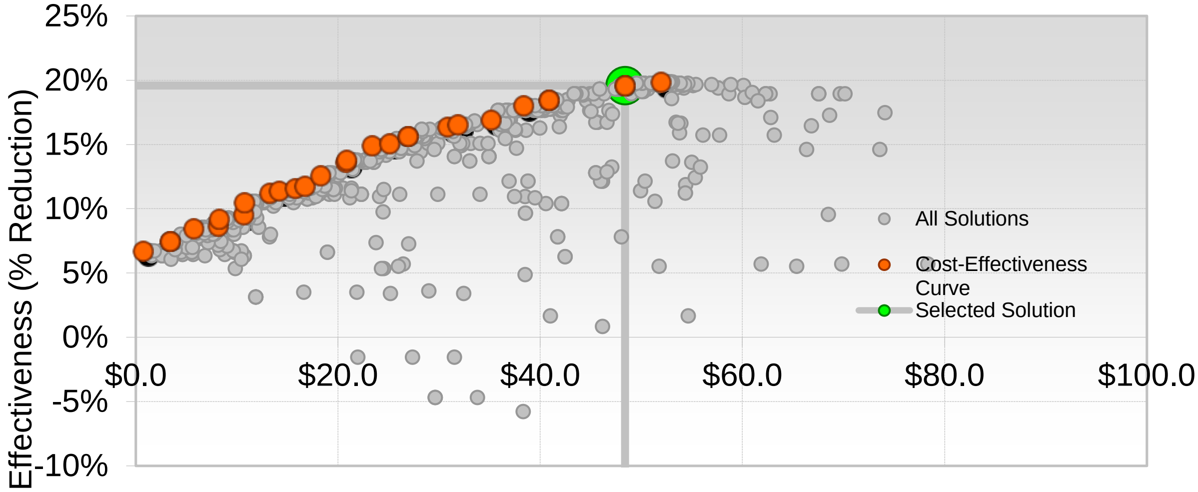


Figure 34. Figures showing cost-effectiveness results for Green only, Cistern, 0% Pervious Treatment (Type D Soils).



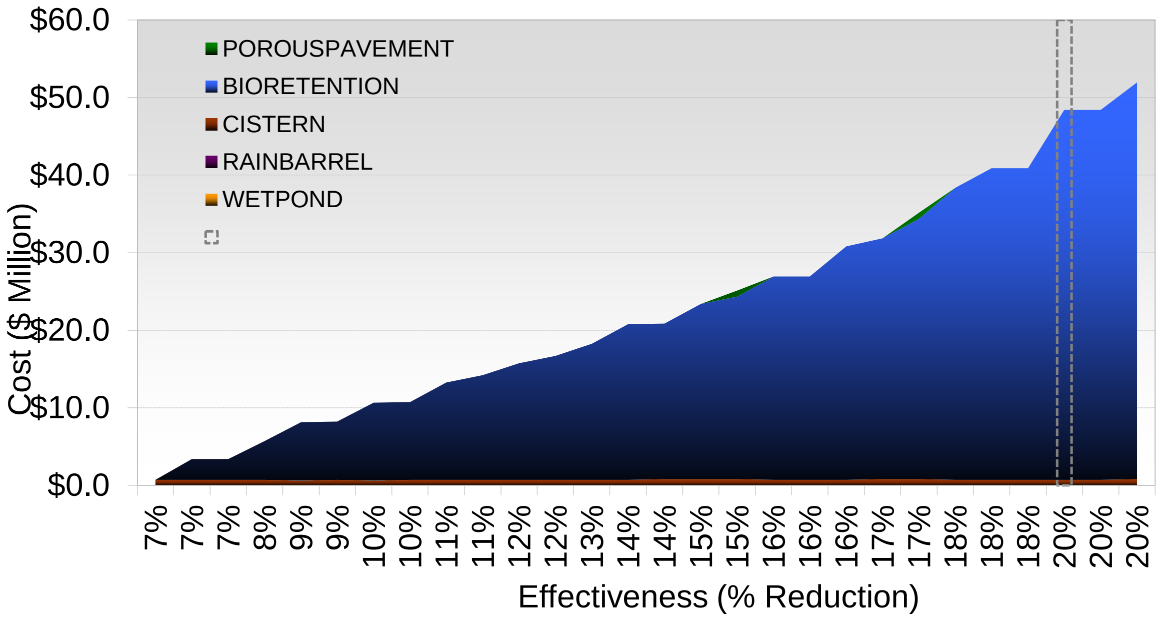


Figure 35. Figures showing cost-effectiveness results for Green only, Cistern, 80% Pervious Treatment (Type D Soils).

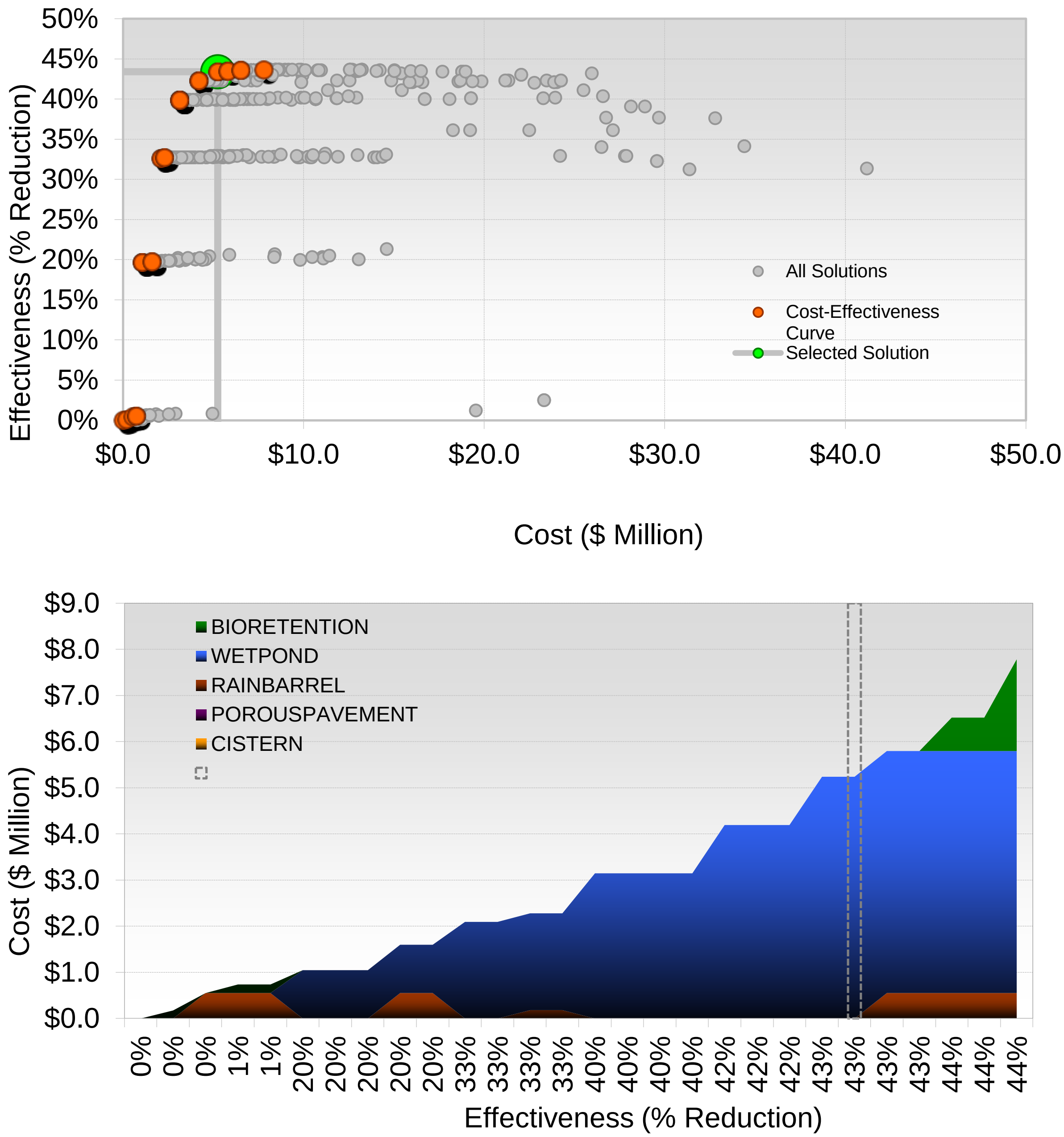


Figure 36. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 0% Pervious Treatment (Type D Soils).

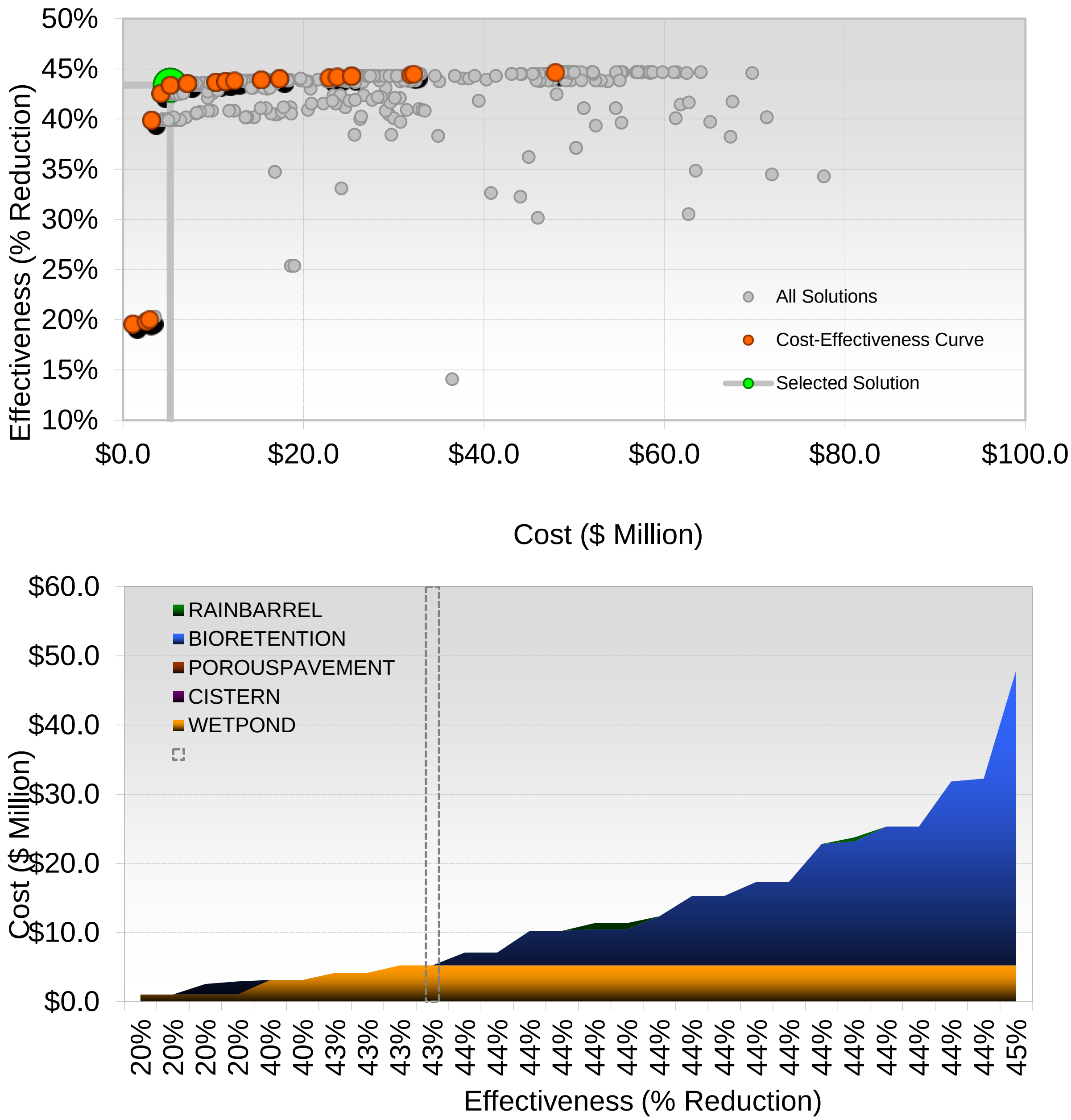
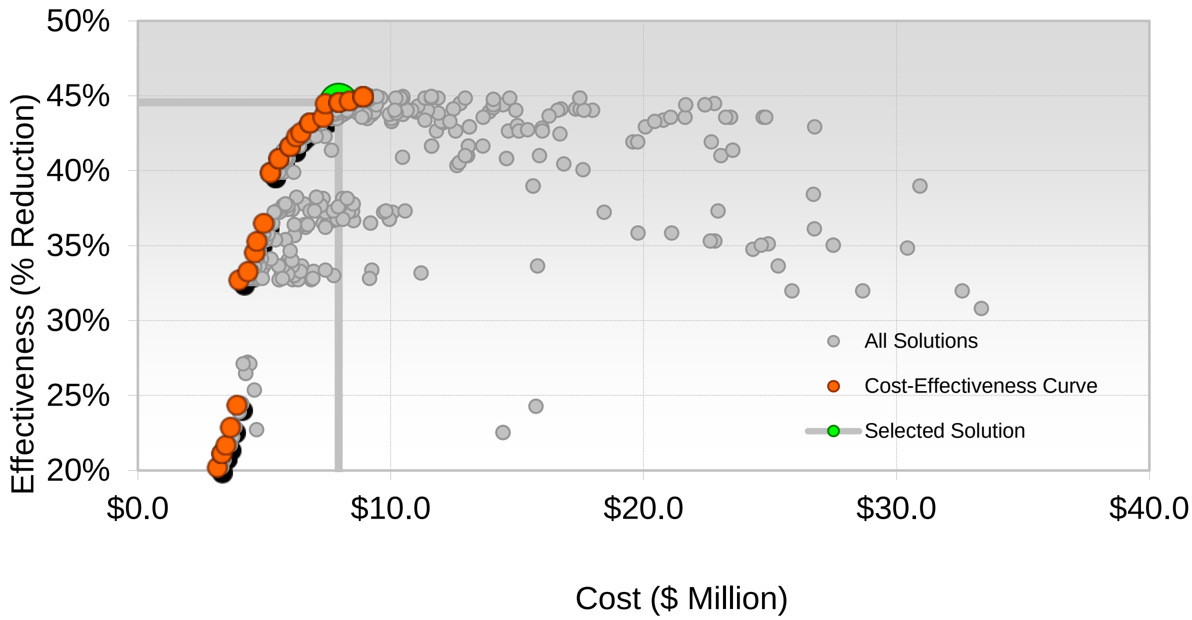


Figure 37. Figures showing cost-effectiveness results for Green+Gray, Rain Barrel, 80% Pervious Treatment (Type D Soils).



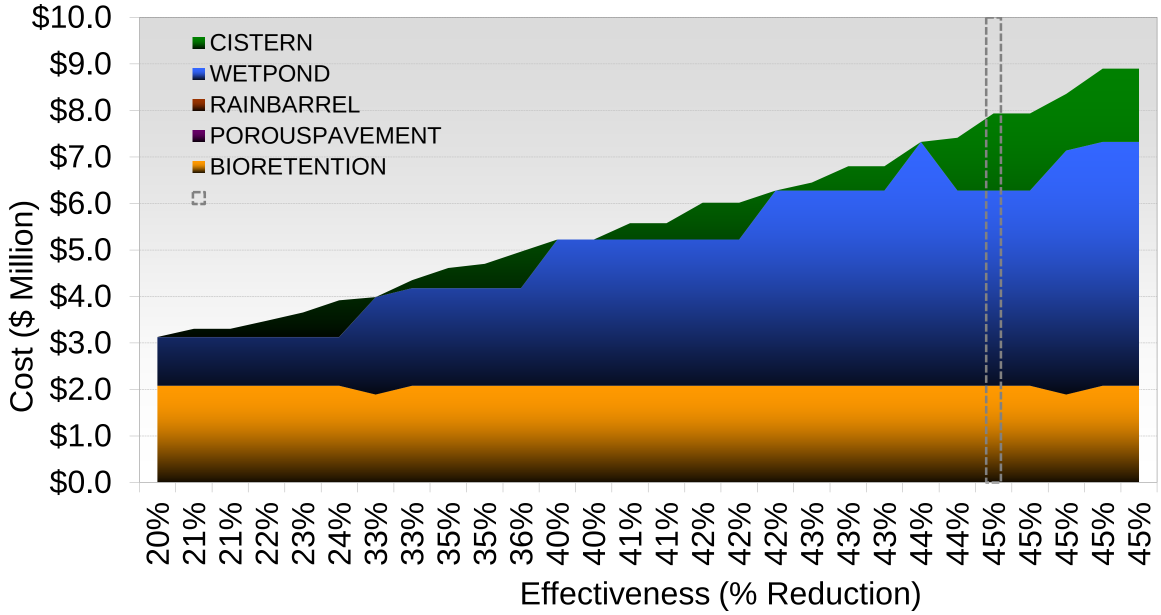
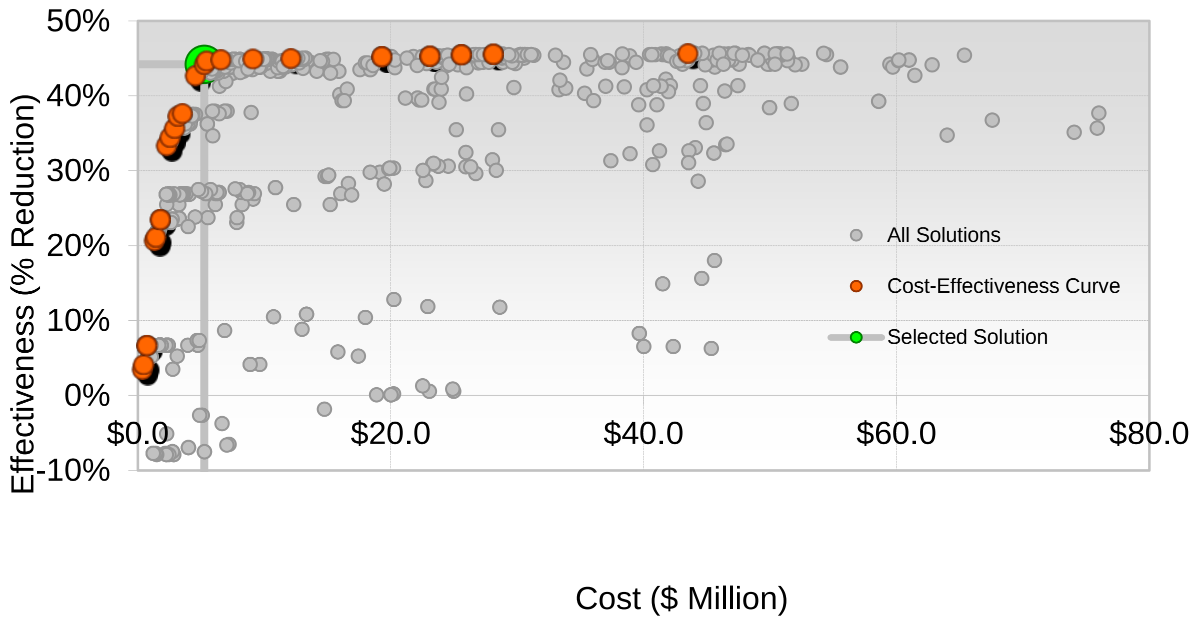


Figure 38. Figures showing cost-effectiveness results for Green+Gray, Cistern, 0% Pervious Treatment (Type D Soils).



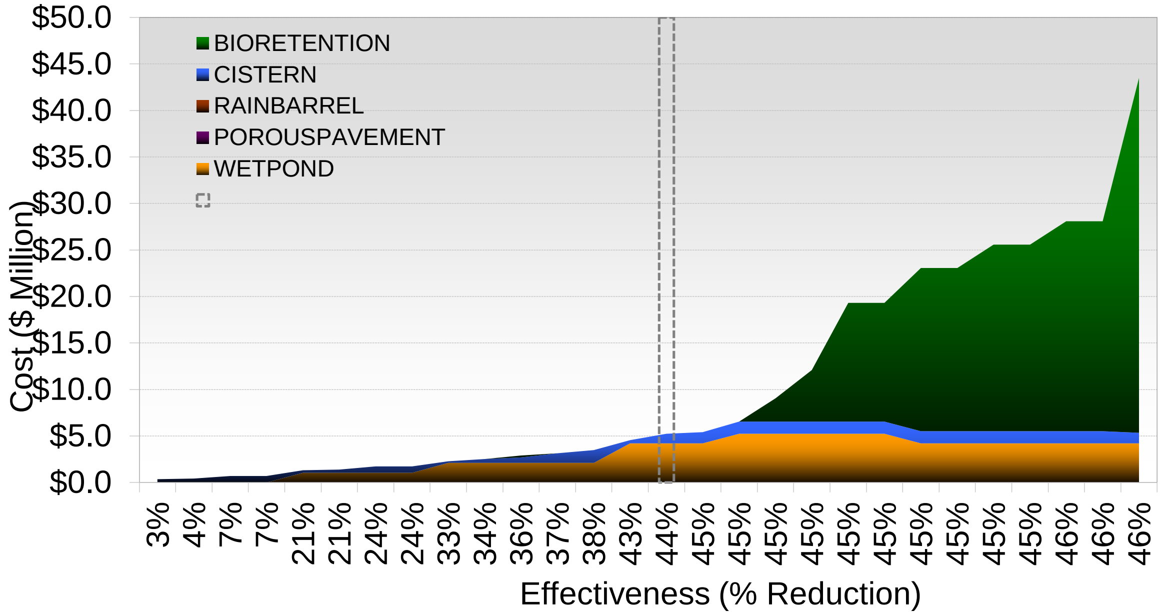


Figure 39. Figures showing cost-effectiveness results for Type D Soils, Green+Gray, Cistern, 80% Pervious Treatment (Type D Soils).